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FERROXPLANA *), HEXAGONAL FERROMAGNETIC IRON-OXIDE COMPOUNDS FOR VERY HIGH FREQUENCIES

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Among high-frequency soft magnetic materials, large-scale use is made of ferroxcube. The upper frequency limit of ferroxcube lies at about 100 Mc/s. New groups of soft magnetic materials have now been developed in the Philips Laboratories at Eindhoven, which may be used at considerably higher frequencies. Like ferroxcube and ferroxdure, these materials are prepared by the sintering of metal oxides. In this article the composition and some of the properties of the new materials are discussed.

The behaviour of ferroxcube materials at high frequencies is briefly as follows [1]. For a number of applications the *initial permeability* μ_i, i.e. the permeability in a weak magnetic field, is important. For a given type of ferroxcube, μ_i remains constant up to a certain limiting frequency, which may lie somewhere between 1 Mc/s and 100 Mc/s. If the frequency is raised above this limit, μ_i decreases and the magnetic losses show a sharp increase.

The product of the initial permeability at low frequency and the frequency at which this permeability begins to decrease is practically the same for the various types of ferroxcube. Snoek [2][3] has explained this as follows. Considered magnetically, the material is divided into a large number of small regions, viz. the Weiss domains. Each domain is magnetized to saturation and this magnetization is bound by a certain restoring couple to a given preferred direction. If, due to some cause, the direction of magnetization is temporarily deflected from the preferred direction, then, owing to the restoring couple and to the fact that the magnetic moment is associated with a mechanical angular momentum (electron spin), the magnetization vector will precess about the preferred direction with a frequency f_r proportional to the strength of restoring couple [4]. If an external alternating magnetic field is applied, a resonance effect occurs as the frequency approaches f_r, which is responsible for the above-mentioned large magnetic losses and the decreased permeability. On the other hand there is the fact that in ferroxcube materials the initial permeability at low frequency μ_i — being presumably mainly due to a rotation of the magnetization vector in each Weiss domain — is likewise essentially determined by the strength of the restoring-couple binding the magnetization to the preferred direction. The susceptibility χ_i at low frequency, which is equal to $\mu_i - 1$ †), is inversely proportional to this restoring couple, so that the product $\chi_i f_r$ may be expected to be a constant, virtually independent of the type of ferroxcube. The value of this product as derived from a quantitative study is in good agreement with the value found experimentally.

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*) Ferroxplana, with the a pronounced as in the word plane.

[1] See e. g. J. J. Went and E. W. Gorter, Philips tech. Rev. 13, 181-208, 1951/52.

[2] J. L. Snoek, Nature 160, 90, 1947.

[3] J. L. Snoek, Physica 14, 207-217, 1948.

[4] For a more detailed explanation, see H. G. Beljers and J. L. Snoek, Philips tech. Rev. 11, 313-322, 1949/50.

†) *Editoral note:* This is valid in the rationalized Giorgi system of units. In the c.g.s. electromagnetic system $\chi_i = (\mu_i - 1)/4\pi$. In this article μ_i is used to represent the *relative* initial permeability with respect to that of free space μ_0. Quantities expressed in the c.g.s. system will be placed between square brackets. In the rationalized Giorgi system the magnetization M is given by the formula:

$$B = \mu_0 (H + M).$$

The relation between χ_i and f_r imposes an absolute frequency limit on the application of the various ferroxcubes as a soft magnetic material. The frequency at which the material is to be used must lie below f_r. Because of the constant value of the product $\chi_i f_r$, very high values of f_r imply that the initial permeability will be only of the order of unity, so that there is no point in using this material.

In this article we shall deal with new ferromagnetic materials which, like ferrocube, are non-metallic in nature and of high resistivity and can therefore be used at high frequencies. In these materials, also, the magnetization has certain preferred directions. In some of these materials, however, the strength of the restoring couple depends also upon the *direction* in which the magnetization is deflected from its position of equilibrium. For a similar case Snoek 3) pointed out the theoretical possibility of evading the above relation between χ_i and f_r. This is indeed possible with the new materials; among them, in fact, are soft magnetic materials that can be used up to far higher frequencies than ferroxcube; they possess e.g. a frequency-independent intitial permeability of approximately 10 up to about 1000 Mc/s. It is proposed to coin the word *ferroxplana* as a generic name for these materials. The significance of this name will reveal itself in a later stage of this article.

Let us first examine the chemical composition of the new compounds. We shall then deal with their magnetic properties, with particular attention to the phenomenon of ferromagnetic resonance in the specific case where the magnetization in different directions is bound to varying degrees with the position of equilibrium.

Chemical composition of the new compounds

The new materials are compounds of the oxides BaO, Fe_2O_3 and MeO, Me representing one of the small divalent ions of Mn, Fe, Co, Ni, Zn or Mg, or a mixture of these. The materials are prepared by heating specific mixtures of these oxides for a given time at a temperature of 1200-1400 °C, so that a sintered ceramic product is obtained.

The composition of these compounds can be represented in a triangle, the vertices of which are formed by the constituent oxides (*fig. 1*). The points S, M, and B on the sides of this triangle represent the following known compounds:

S: $MeFe_2O_4$, the ferrites with the cubic spinel structure (ferroxcube).

M: $BaFe_{12}O_{19}$, with the hexagonal magnetoplumbite structure, the main component of the permanent magnet material ferroxdure.

B: $BaFe_2O_4$, a non-ferromagnetic compound.

In earlier work on permanent magnet materials, the compound $BaFe^{II}_2Fe^{III}_{16}O_{27}$ was found within the above-mentioned triangle 5). This compound is represented in fig. 1 by the point **W** on the line connecting **M** and S, Me in the latter representing an Fe^{II}-ion. The presence of this compound led to investigations to see whether a series of corresponding compounds could be prepared in which other Me-ions were substituted for the Fe^{II}-ions. (A similar substitution is possible with $Fe^{II}Fe^{III}_2O_4$, resulting in S-type compounds, the ferroxcubes.)

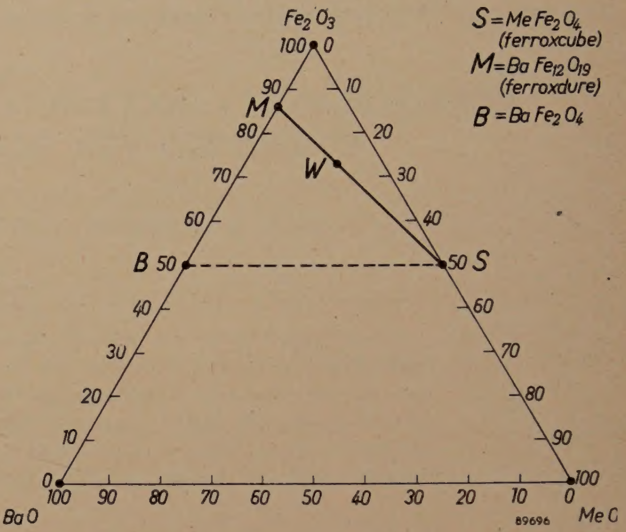

Fig. 1. The composition of the **W** compounds is represented by a point within the triangle. The symbol Me represents one of the divalent ions Mn, Fe, Co, Ni, Zn or Mg or a mixture of these. The known materials ferroxcube (S), ferroxdure (M) and $BaFe_2O_4$ (B) are represented by points on the sides of the triangle.

The formation of such "substituted" **W** compounds can be studied by means of X-ray powder diffraction studies of the final product. Since, however, **M** and **W** are structurally closely related (see 5)), small quantities of **M** which can appear as a second phase due to incomplete chemical reaction cannot be easily identified in the X-ray diagrams (see *fig. 2*). This difficulty can be avoided as explained below.

Like the **M** compounds, the **W** compounds are ferromagnetic with a hexagonal crystal structure. The preferred direction of magnetization is parallel to the hexagonal axis. The small crystals in powdered materials will therefore assume such an orientation in a magnetic field that the hexagonal axis of each crystal becomes more or less parallel to the lines of force. A few drops of a suspension of

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5) H. P. J. Wijn, Nature **170**, 707, 1952.
P. B. Braun, Nature **170**, 708, 1952.

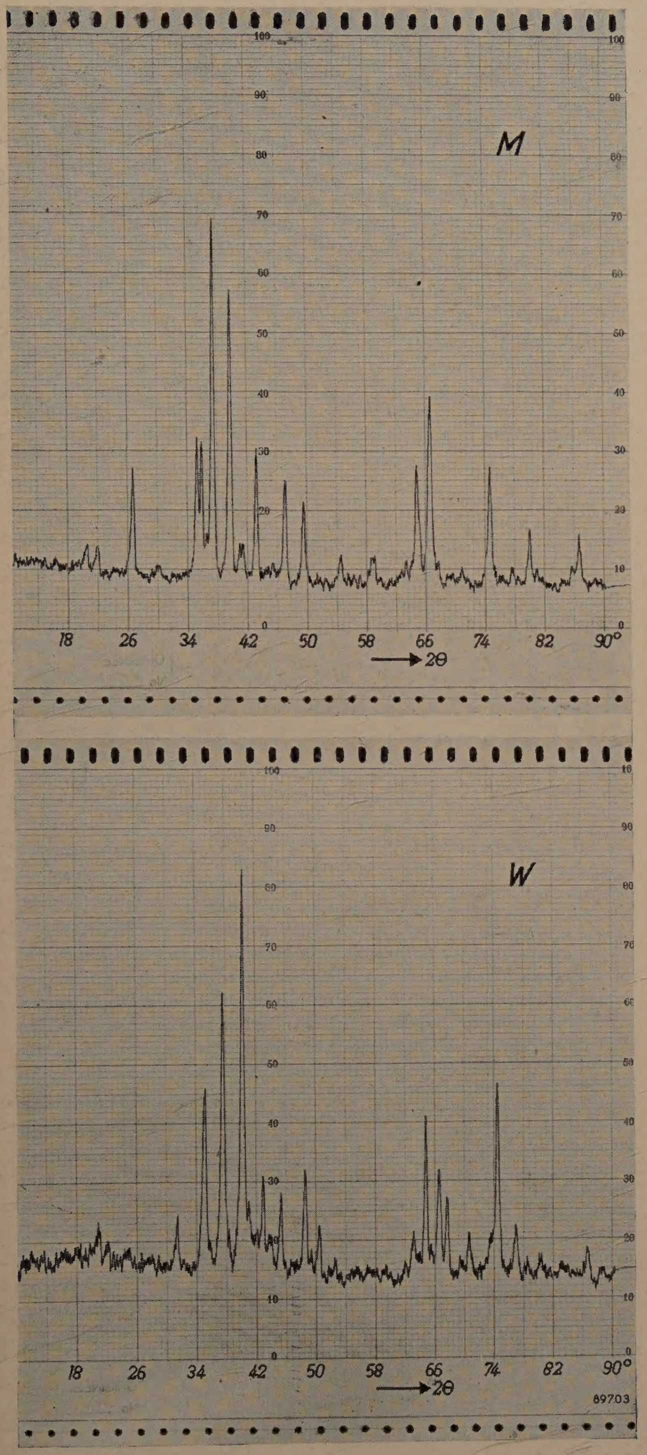

Fig. 2. X-ray diffraction diagrams of powders of **M** and **W** compounds, taken with Co Kα radiation.

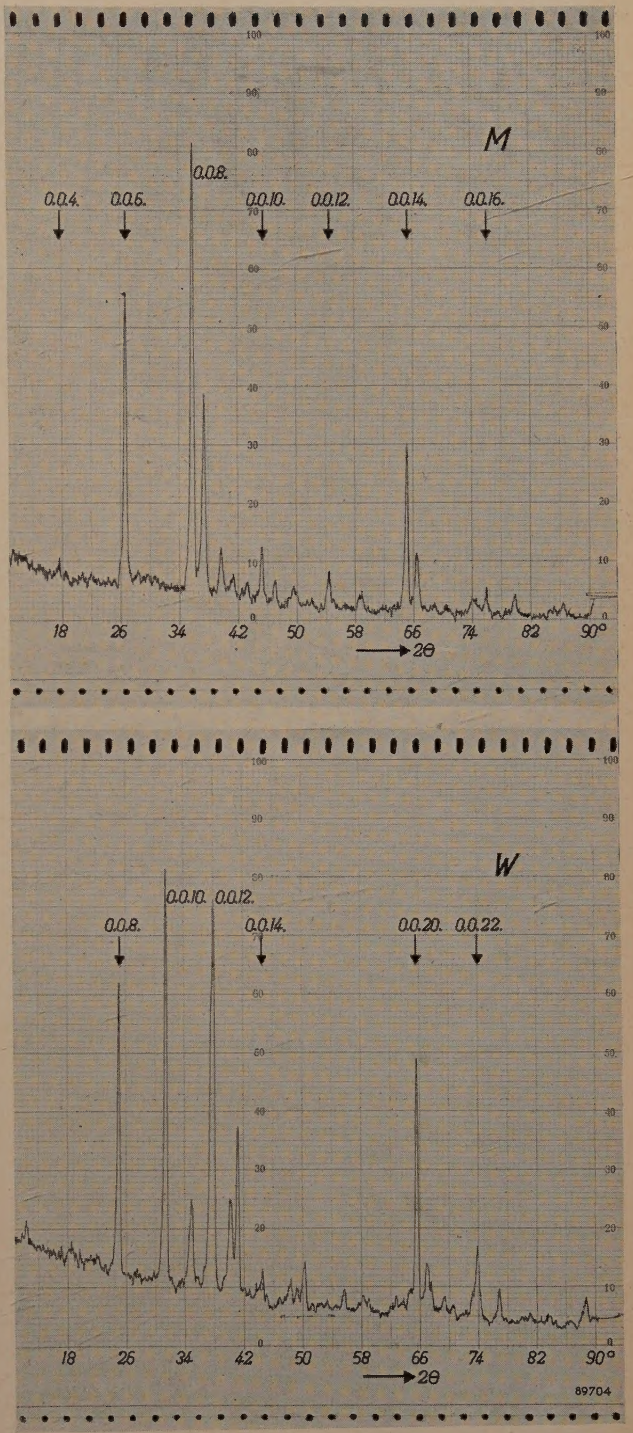

Fig. 3. X-ray diffraction diagram of magnetically oriented powder specimens of **M** and **W**. The reflections from the basal planes 0.0.*l* are intensified with respect to those of fig. 2.

the powdered specimen in a solution of a binder are now applied on a glass plate, after which a strong magnetic field is applied perpendicular to this plate. When the solvent of the binder is allowed to evaporate completely before the magnetic field is switched off, the crystals will remain with their hexagonal axes perpendicular to the glass surface. In the X-ray diffraction pattern of such a specimen obtained with the diffractometer [6]), the X-ray reflections from the planes perpendicular to the hexagonal axis appear much intensified, whereas the other reflections have nearly disappeared. This greatly simplifies the diagram, see *fig. 3*.

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[6]) The diffractometer is well-suited to the investigation of flat specimens such as this; cf. W. Parrish, E. A. Hamacher and K. Lowitzsch, Philips tech. Rev. **16**, 123-133, 1954/55.

These simplified diagrams are characteristically different for M and W, so that now a small quantity of one of these compounds can be easily identified in the presence of a large quantity of the other compound.

This method makes it possible to examine with great accuracy the reaction products formed by the sintering of the oxide mixtures. With this sensitive measure of the reaction, it was possible to improve the process such that pure compounds could be obtained, in which the Fe^{II}-ions are entirely or partly replaced by other ions. We shall henceforth designate the separate compounds of this group, which is generally indicated by the symbol **W**, by prefixing the **W** with the symbols of the divalent ions in question. NiZnW, for instance, stands for the compound $BaNiZnFe_{16}O_{27}$.

A general examination of the reaction products obtained from mixtures of BaO, Fe_2O_3 and MeO revealed that other ferromagnetic compounds are also formed. The X-ray diagrams of these compounds were found to be so similar to those of **M** and **W** that, with the aid of them alone, it was impossible to establish with what compositions of oxide mixtures they could be precisely synthesized. The method of orientation in a magnetic field was therefore again used, and the result was once more a characteristic simplification of the diffraction patterns. This made it possible to establish that *two* more compounds occur, indicated in the triangle by the points Y and Z (see *fig. 4*), with the chemical formulae:

$$Ba_2Me_2Fe_{12}O_{22} \quad ^{7)} \text{ for } \mathbf{Y}$$

and

$$Ba_3Me_2Fe_{24}O_{41} \quad \text{ for } \mathbf{Z}.$$

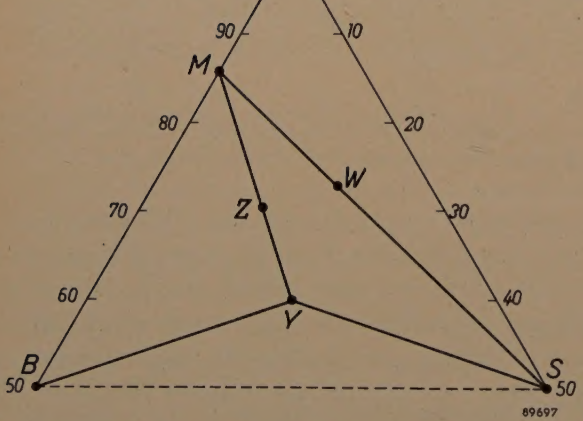

Fig. 4. Situation of the points for the new compounds **Y** and **Z** in the top section of the triangle of fig. 1.

Further investigations showed that these compounds possess hexagonal crystals tructures closely related to those of **M** and **W** (see Appendix).

If the various divalent ions are substituted for Me, we obtain compound *groups*, which will be called the **Y** group and the **Z** group. The separate compounds in these groups will be designated in a manner similar to those in the **W** group.

Preferred direction and preferred plane

The diffraction patterns of the magnetically oriented specimens (*fig. 5*) show that the crystals of the **Z** and the **Y** specimens have a different orientation relative to the magnetic field. For most **Z** specimens the hexagonal axis (c-axis) is found to be parallel to the magnetic field; the spontaneous magnetization of these compounds is therefore directed along the c-axis. This axis is a *preferred direction*, just as with the **M** and the **W** group. With all **Y** specimens on the other hand the hexagonal axis is perpendicular to the magnetic lines of force, the directions of the other axes being yet arbitrary; this means that the spontaneous magnetization of the **Y** compounds lies in a plane *perpendicular* to the c-axis. In this plane, which we call the *preferred plane*, the magnetization can have virtually any direction.

Further investigation has revealed that a preferred plane does not occur solely with the **Y** group, but also with those compounds of the **Z** and **W** groups in which Co-ions are completely or partly substituted for Me. *Table I* indicates for all new compounds in which one specific type of ions are substituted for Me, whether a preferred direction (↑) or a preferred plane (⊥) occurs. The occurrence of a preferred plane is of great consequence as regards the magnetic behaviour, as we shall see later. For the various groups of iron oxide compounds with a preferred plane of magnetization the generic name of ferroxplana is proposed. *Table II* gives the saturation magnetization and the Curie temperature of some of the new materials, both with a preferred plane and with a preferred direction.

The occurrence of a preferred plane can also be expressed more quantitatively. If a preferred direction occurs in a hexagonal structure, then the energy E required per unit volume to deflect the

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7) This might be written in simpler form by halving the number of atoms, thus obtaining $BaMeFe_6O_{11}$. Nevertheless the above formula is preferred, owing to the fact that, like those of the other compounds discussed, it indicates the correct number of atoms per "structural unit", as will be seen later in this article.

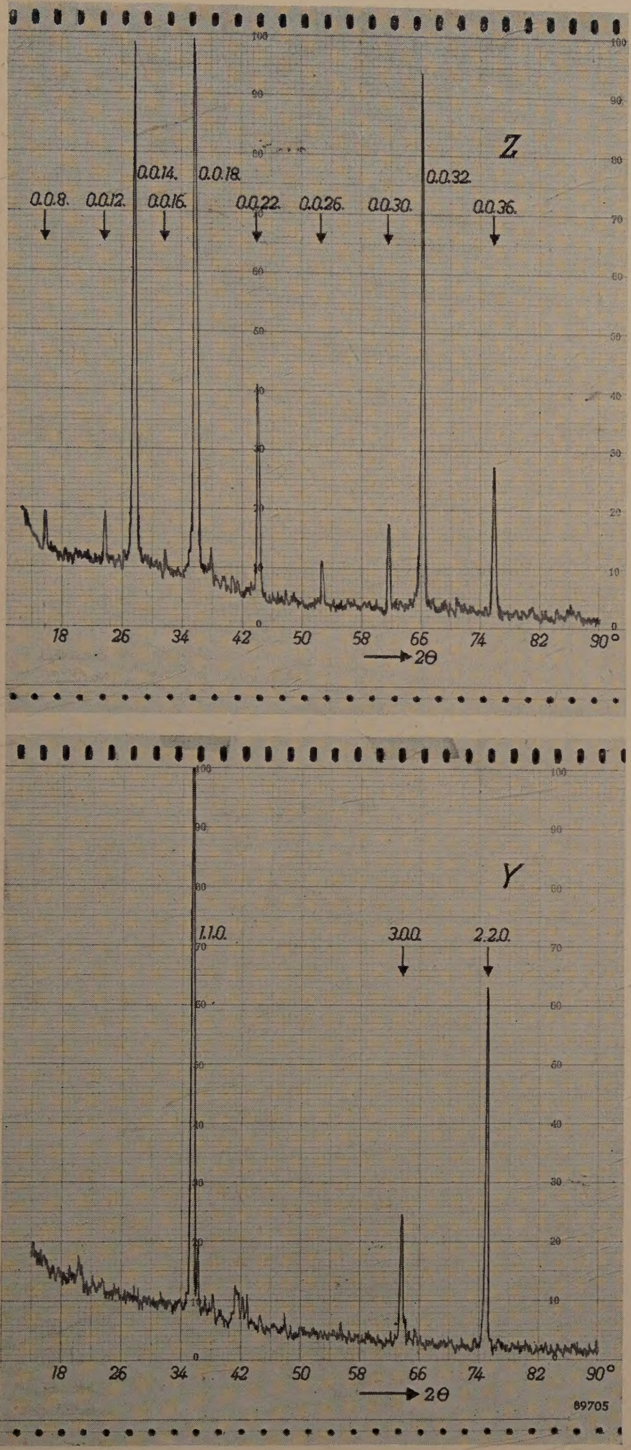

Fig. 5. X-ray diffraction diagrams of magnetically oriented powder specimens of **Z** and **Y**. With the **Z** compounds the reflections from the 0.0.*l* planes (basal planes) are again intensified; with **Y** compounds, reflections from the *h.k.*0 planes (parallel to hexagonal axis) are intensified.

magnetization through an angle Θ with respect to the direction of the hexagonal axis, can be roughly expressed by [8]):

$$E = K \sin^2 \Theta. \quad \ldots\ldots \quad (1)$$

Table I. Compounds with a preferred direction (↑) or a preferred plane (⊥).

Group	Divalent ion substituted for Me					
	Mn	Fe	Co	Ni	Zn	Mg
W	↑	↑	⊥	↑	↑	↑
Z	↑	↑	⊥	↑	↑	↑
Y	⊥	⊥	⊥	⊥	⊥	⊥

The quantity K is termed the crystal anisotropy constant. We see that for positive K, the direction $\Theta = 0$, i.e. the c-axis, is the direction of minimum energy. In the case of a preferred plane the energy minimum occurs for $\Theta = 90°$, which means that K in (1) is now negative. We can thus express the occurrence of a preferred plane by saying that the compounds in question have a negative crystal anisotropy. We could also say that in such a case the direction $\Theta = 0$ is an "abhorred direction" for the magnetization.

Table II. Saturation magnetization $\mu_0 M$ at 20 °C and Curie temperature T_c for some of the new materials. For comparison the values of $\mu_0 M$ and T_c for ferroxcube 4E are also given.

Material	$\mu_0 M$ in 10^{-4} Wb/m² [$4\pi M$ in gauss]	T_c in °C
$\mathbf{Mn_2W}$	4000	410
CoFeW	4500	430
ZnFeW	4800	422
$\mathbf{Ni_{0\cdot5}Zn_{0\cdot5}Fe_1W}$	4600	425
$\mathbf{Co_2Y}$	2900	340
$\mathbf{Mg_2Y}$	1400	300
$\mathbf{Co_2Z}$	3500	400
Ferroxcube 4E	3280	595

If we replace Co in the **W** or **Z** group by a mixture of Co and an increasing quantity of another ion, e.g. Zn, then we notice that at a certain percentage of Zn the preferred plane changes into a preferred direction. The crystal anisotropy, initially negative, gradually changes with increasing Zn-content towards a positive value.

One may also consider the crystal anisotropy energy of the cubic ferromagnetic materials, such as ferroxcube (spinel structure). Because of the cubic structure, however, the energy E must now be invariant with respect to the edges of the cube, the latter being equivalent. Let α_1, α_2 and α_3 be the direction cosines of a given direction with respect to the three crystal axes, then the simplest formula to replace (1) is;

$$E = K' \left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2\right) \quad \ldots\ldots \quad (2)$$

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[8]) See J. J. Went, G. W. Rathenau, E. W. Gorter and G. W. van Oosterhout, Philips tech. Rev. **13**, 194-208, 1951/52.

This formula is an approximation. We can derive from it that K' is positive when the edges of the cube are the preferred directions and negative when the body diagonals are the preferred directions.

With these ferrites we likewise find that the Co-substitution gives rise to a change in the sign of K': K' is positive for cobalt ferrite [9]) and negative for all other ferrites. If we compare the structures of the cubic and the hexagonal compounds and consider both as the close-packing of spheres of oxygen ions, then the direction of one of the body diagonals of the cubes is equivalent to the c-axis of the hexagonal structure. If these are the preferential directions for each structure (and this is true for both types of compounds if no Co is present, apart from the Y-group compounds), then the anisotropy is positive in the hexagonal substances, but negative in the cubic ones. The difference in sign for the anisotropy when comparing cubic and hexagonal compounds arises from the definition of K and K' in (1) and (2) respectively. Since these definitions have become generally adopted, we shall continue to use them, in spite of the possible confusion which may arise.

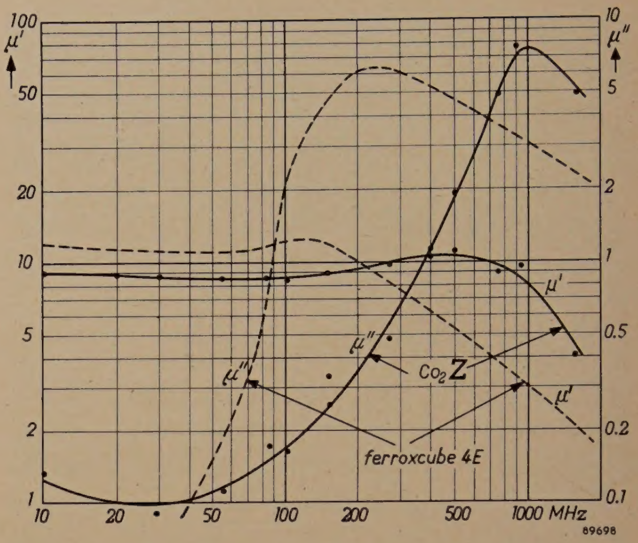

Fig. 6. The real part μ' and the imaginary part μ'' of the initial permeability μ_i, plotted as a function of the frequency f for the materials Co_2Z (full lines) and the cubic nickel ferrite ferroxcube 4E (dotted lines).

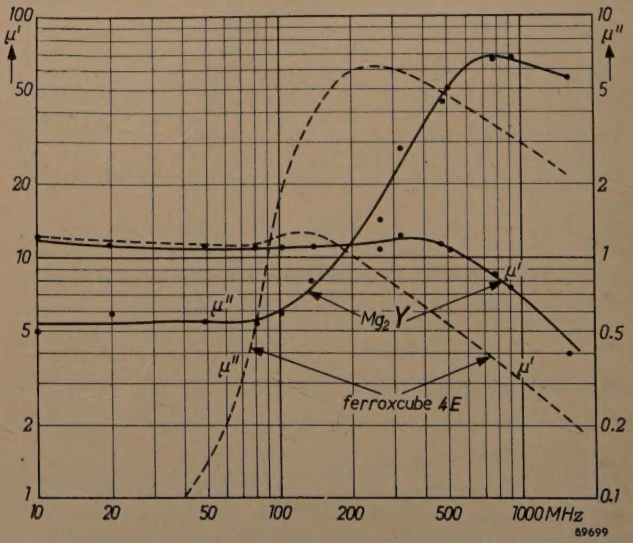

Fig. 7. μ' and μ'' as functions of f for the materials Mg_2Y (full lines) and ferroxcube 4E (dotted lines).

The importance of materials with preferred plane

The fields of application of these hexagonal compounds depend on whether they have a preferred direction or a preferred plane.

For compounds with a *preferred direction*, the corresponding crystal anisotropy is as a rule substantially greater than that of cubic compounds (ferroxcube). The magnetization is then rigidly bound to that direction, which renders such materials in principle suitable for application as a permanent magnet material, with properties similar to ferroxdure (M).

For compounds with a *preferred plane*, the magnetization is virtually free to assume any direction in that plane, or at least the direction is not determined by the value of K, which only specifies the energy required for a rotation *out of* the plane. There are, of course, other forms of crystal anisotropy, and moreover the stress anisotropy and the shape anisotropy (see [1])), which cause a preferred direction of magnetization within the plane and oppose rotation within the plane, but these are as a rule small (they also occur in ferroxcube). Ferroxplana materials are therefore unsuitable for use as permanent magnets. On the other hand, they may in principle have a large permeability and are thus suitable as soft magnetic materials. Owing to their non-metallic character, these materials have fields of application similar to the ferroxcubes, particularly for high frequencies. It is found that the ferromagnetic resonance effect, which places a frequency limit on the application of magnetic materials, occurs with many ferroxplana materials only at far higher frequencies than with ferroxcube. As an example, *fig. 6* shows the experimentally determined initial permeability μ_i of the compound Co_2Z plotted as a function of the frequency. The permeability of the cubic nickel ferrite, ferroxcube 4E is also shown. The real part μ' and the imaginary part μ'' of the initial permeability (see e.g. [1])) are given; μ'' is proportional to the losses, and the loss angle δ is given by $\tan \delta = \mu''/\mu'$. The diagram shows that, although the permeability at low frequency is about the same for both materials, the value of μ' for Co_2Z at 1000 Mc/s hardly differs from that at low frequency, whereas the value of μ' for ferroxcube 4E at 1000

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[9]) R. M. Bozorth, E. F. Tilden and A. T. Williams, Phys. Rev. **99**, 1788-1789, 1955.

Mc/s has nearly dropped to unity. The difference in ferromagnetic resonance frequency can also be seen in the curves for μ''. If, for example, the frequencies are compared at which $\mu''/\mu' = 0.1$, it can be seen that Co_2Z can be used up to a frequency considerably higher (e.g. 5×) than ferroxcube 4E.

Fig. 7 similarly compares ferroxcube 4E with the compound Mg_2Y. Here too, we find the same characteristic of the initial permeability of Mg_2Y remaining constant to a higher frequency. Other ferroxplana materials show similar results.

In the following section this behaviour of ferroxplana will be considered theoretically.

Ferromagnetic resonance in materials with a preferred plane

The resonance frequency

In the introduction it has been shown that the ferromagnetic resonance in cubic ferrites depends on the tightness with which the magnetization is bound to the preferred direction and to the fact that a magnetic moment is fundamentally associated with a mechanical angular momentum. This can be quantitatively analysed as follows. The couple tending to restore the magnetization to the preferred direction can be described for small deviations from this direction by introducing an apparent internal magnetic field H_A in this direction, the anisotropy field, which is given by:

$$H_A = \frac{2K}{\mu_0 M},$$

M representing the saturation magnetization. That this field is equivalent to the anisotropy can be seen from the fact that the couple $\mu_0 \vec{M} \times \vec{H}_A$ occurring when the magnetization is turned through a small angle Θ from the preferred direction, has the appropriate value of $2K\Theta$. This couple is equal to the rate of change in the angular momentum, so that

$$\vec{M} \times \vec{H} = \frac{\dot{\vec{M}}}{\gamma}, \quad . \; . \; . \; . \; . \quad (3)$$

where γ is the gyromagnetic ratio, i.e. the ratio of the magnetic moment to the corresponding angular momentum (0.221 Mc/s per A/m. [17.6 Mc/s per Oe]). From this the resonance frequency f_r' can be easily derived:

$$2\pi f_r' = \gamma H_A \quad . \; . \; . \; . \; . \; . \quad (4)$$

Let us now consider the more complex resonance in materials with a preferred plane. The situation is illustrated by *fig. 8*, in which the xy-plane represents the preferred plane. Let us assume that the magnetization within this plane has an additional (weak) preference for the x-direction, which may be described as an anisotropy field H_{A1}. This anisotropy refers to the case where M is turned out of the x-direction towards the y-direction, i.e. within the preferred plane, as shown in fig. 8*a*. If M is turned towards the z-direction, so that it is moved out of the preferred plane (fig. 8*b*), the far greater anisotropy field H_{A2} is involved.

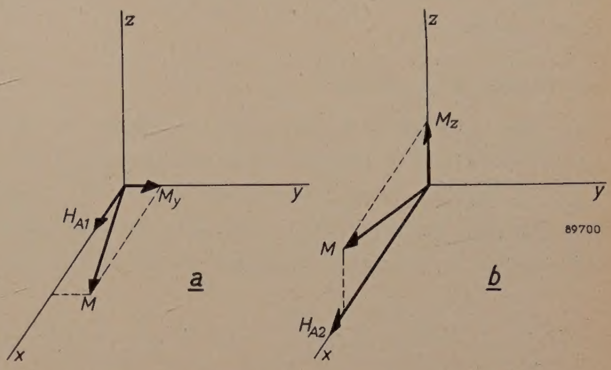

Fig. 8. *a*) If the magnetization is deflected *within* the preferred plane (xy-plane) the anisotropy field H_{A1} is involved. *b*) A deflection *out of* the preferred plane involves the far stronger field H_{A2}.

Under the influence of the two anisotropy fields a deviation of M from the x-direction will again cause it to describe a precession with a certain as yet unknown frequency f_r. The situation of fig. 8*a* can be represented by:

$$\gamma M_y H_{A1} = \dot{M}_z \quad . \; . \; . \; . \; . \; . \quad (5)$$

whilst the situation of fig. 8*b* can be put as:

$$\gamma M_z H_{A2} = -\dot{M}_y \quad . \; . \; . \; . \quad (6)$$

Differentiating (5) and substituting for $\dot{M}_y$ from (6), we obtain

$$\gamma^2 H_{A1} H_{A2} M_z + \ddot{M}_z = 0 \quad . \; . \; . \quad (7)$$

whilst a similar equation can be derived for M_y. The frequency is now given by:

$$2\pi f_r = \gamma \sqrt{H_{A1} H_{A2}} \quad . \; . \; . \; . \quad (8)$$

f_r is thus proportional to the geometrical mean of the anisotropy fields [3] [10]). If these fields are equal, we clearly arrive at formula (4) again.

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[10]) C. Kittel, Phys. Rev. **73**, 155-161, 1948.

It is apparent from (8) that the resonance frequency for materials with a preferred plane can be far higher than that for materials having a cubic structure. The anisotropy field H_{A1} for deviation of the magnetization *within* the preferred plane is of the same order of magnitude as the H_A of ferroxcubes, whereas the anisotropy field for a deflection *out of* the preferred plane is generally much larger than H_{A1}.

In figs. 6 and 7 it was shown that ferroxplana not only possesses a far higher resonance frequency than ferroxcube, but also has about the same initial permeability. A theoretical study, briefly reproduced in the following section, leads to the same conclusion.

The initial permeability

In the general case that the coupling of the magnetization to a preferred direction can be described in terms of two anisotropy fields H_{A1} and H_{A2}, the susceptibility of a crystal in the direction of the three main axes (see fig. 8) can be written as:

$$\chi_{xx} = 0;\ \chi_{yy} = \frac{M}{H_{A1}};\ \chi_{zz} = \frac{M}{H_{A2}}.$$

These expressions are based on the assumption that for these materials, as for ferroxcube, the susceptibility is primarily governed by rotation processes. For a polycrystalline material with a random orientation of the crystallites, and disregarding their magnetic interaction, the resultant susceptibility is given by:

$$\chi = \frac{1}{3}\left(\frac{M}{H_{A1}} + \frac{M}{H_{A2}}\right). \quad . \quad . \quad . \quad . \quad (9)$$

Materials such as ferroxcube and also ferroxdure form a special case where $H_{A1} = H_{A2}\ (= H_A)$, so that formula (9) is simplified into

$$\chi_{\uparrow} = \frac{2}{3}\frac{M}{H_A}. \quad . \quad . \quad . \quad . \quad . \quad (10a)$$

The large initial permeability of ferroxcubes is attributable to the fact that their H_A is small (about 10^2 - 10^4 A/m [1 — 100 Oe]).

For the materials with a preferred plane described here, $H_{A2} \gg H_{A1}$, H_{A1} being comparable in magnitude to H_A of ferroxcube, whilst H_{A2} is of the same order of magnitude as H_A of ferroxdure (approx. 10^6 A/m [approx. 10^4 Oe]). A good approximation is thus obtained by:

$$\chi_{\perp} = \frac{1}{3}\frac{M}{H_{A1}}. \quad . \quad . \quad . \quad . \quad . \quad (10b)$$

This formula shows that also with ferroxplana substantial permeability values may occur in principle, since M assumes values comparable to those of ferroxcube (see table II).

Finally we shall illustrate the essential difference in behaviour between ferroxplana and ferroxcube in a manner similar to that used by Snoek (for single crystals) ³). Combining (8) and (9) produces the formula:

$$2\pi f_r \chi = \frac{2}{3}\gamma M\left(\frac{1}{2}\sqrt{\frac{H_{A1}}{H_{A2}}} + \frac{1}{2}\sqrt{\frac{H_{A2}}{H_{A1}}}\right). \quad (11)$$

The factor between brackets always amounts to unity for ferroxcubes; this implies that for a given value of the permeability approximately the same limiting frequency is found for all ferroxcubes, as pointed out in the introduction. For the case of $H_{A2} \neq H_{A1}$, such as with ferroxplana, the factor between brackets is always *greater* than unity, to a degree that is dependent upon H_{A2}/H_{A1}. Whenever the permeability values are about equal, this factor immediately indicates to what extent the frequency limit of ferroxplane is raised with respect to that of ferroxcube.

Comparison between theory and experiment

Formula (8) could be tested experimentally for various materials because they could be obtained in the form of single crystals, in which H_{A2} could be directly measured; H_{A1} can be evaluated by means of eq. (10b) from the quantities $\chi_{\perp}$ and M, measured on the sintered materials.

Table III gives a comparison of the values of the resonance frequency obtained from (8) with those measured experimentally. The experimental resonance frequency was defined as the frequency at which the permeability has dropped to half the value at low frequency. The agreement between the theoretical and the measured values may be considered satisfactory.

Table III. Theoretical and measured values of the resonance frequency for two materials.

Material	$\chi_{\perp}$ *) at low freq.	$\mu_0 M$ *) in 10^{-4}Wb/m² [$4\pi M$ in gauss]	H_{A1} in A/m	H_{A2} in A/m	f_r in 10^3 Mc/s	
					computed from (8)	measured
Co_2Z	7	2700	10^4	1.1×10^6	3.7	2.5
Mg_2Y	9	900	0.25×10^4	1.2×10^6	2.1	1.0

*) The values for $\chi_{\perp}$ and M refer to porous sintered materials.

Appendix: The crystal structure of the compounds of the W, Y and Z groups

The crystal structure of the new compounds was determined by means of an X-ray investigation. We shall not enter into the investigation itself [11]), but the results can be briefly summarized as follows. Like **M** and **W**, the **Y** and **Z** compounds have a hexagonal crystal structure, which can be described as the close-packing of spheres of the large oxygen and barium ions. Layers of these ions are perpendicular to the hexagonal axis. In the unit cell each layer contains four large ions. In most layers these are four oxygen ions, but at regular intervals there is a layer with three oxygen ions and one barium ion. In **M** compounds these barium-containing layers occur once in five layers, and in **W** compounds once in seven layers. In **Y** compounds two adjacent layers each contain a barium ion; these double layers are then followed by four oxygen layers. The small metal ions are found in the interstices in the oxygen lattice. Just as with the spinel structure, these are either tetrahedral sites, surrounded by four oxygen ions, or octahedral sites, surrounded by six oxygen ions. In **M** and **W** compounds an additional metal ion occurs in the Ba-containing layer, at a site surrounded by five oxygen ions. These structures can be visualized with the aid of *fig. 9*. This shows a cross section through a plane of symmetry of the structures. In the *c*-direction the cross-section does not extend over the entire length of the unit cell, but over part of it, a so-called "structural unit". From these "structural units" or "blocks" of five, seven and six layers respectively, which we have termed the M_5, W_7 and Y_6 blocks, the unit cells of **M**, **W**, **Y** and also **Z** can be built up as follows.

The unit cells of **M**, **W**, and **Y** can be built up by stacking together two M_5, two M_7 and three Y_6 blocks respectively. In doing this, the blocks must be so turned that the crosses indicated in fig. 9 become centres of symmetry. By placing the block Y_6 in the orientation as it is shown here upon the block M_5 we obtain a block that we shall call Z_{11}. Two Z_{11} blocks then form the unit cell of **Z**, provided they are joined in such a way that the centres of symmetry in one of the boundary layers coincide. Finally it may be observed that the W_7 block can be considered as a stacking of an M_5 block with two layers of the **S** composition. The essentials of the data given above are summarized in *Table IV*.

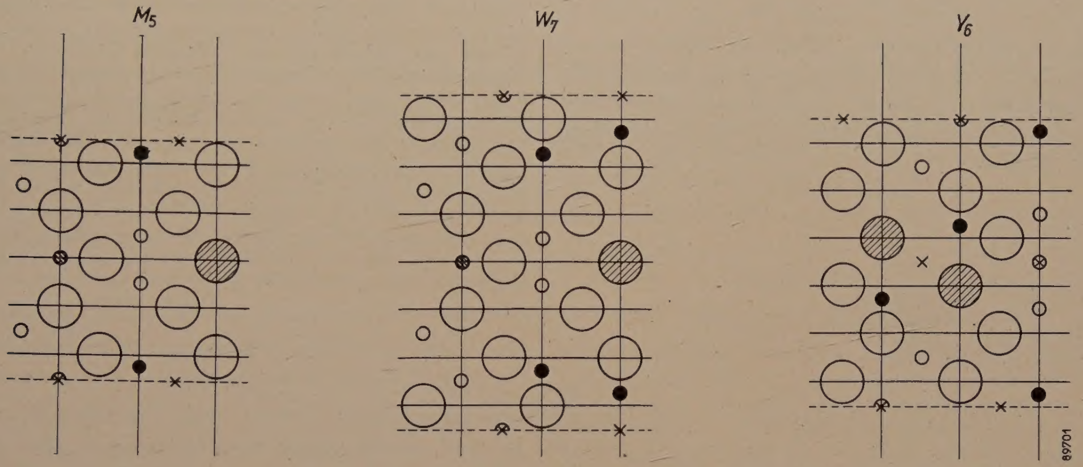

Fig. 9. Cross-section through a plane of symmetry of the "structural units" or "blocks" M_5, W_7 and Y_6. The crosses represent centres of symmetry, the vertical lines are threefold axes of symmetry. All atoms not situated on any of these axes thus occur three times in each block. The complete spatial structure of a block can be obtained by rotating this cross-section e.g. about the central axis of symmetry 120° forward and 120° backward out of the plane. We thus get the layers of four large ions of oxygen (◯) or barium (▨) as mentioned in the text. These layers are indicated by horizontal lines. The small black dots represent metal ions (Me) at the tetradehal sites, the small white circles are metal ions at the octahedral sites, whilst the small hatched circles represent the metal ions surrounded by five oxygen ions.

The diagram shows that the chemical formulae for **M**, **W** and **Y** given above indeed represent the number of ions contained in M_5, W_7 and Y_6 blocks.

Table IV. Chemical formulae and some crystallographical properties of the hexagonal ferromagnetic compounds dealt with.

Group	Formula	Unit cell		
		a-axis in Å	*c*-axis in Å	Structure
M	$BaFe_{12}O_{19}$	5.9	23.3	2 M_5
W	$BaMe_2Fe_{16}O_{27}$	5.9	32.8	2 W_7 = 2(M_5+2S)
Y	$Ba_2Me_2Fe_{12}O_{22}$	5.9	43.5	3 Y_6
Z	$Ba_3Me_2Fe_{24}O_{41}$	5.9	56.0	2 (M_5 + Y_6)

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[11]) P. B. Braun, Crystal structures of a new group of ferromagnetic materials, Philips Res. Rep., to be published shortly.

The values measured for the saturation magnetization of the new compounds are in good agreement with the crystal structures described above. Néel [12]) demonstrated that in ferromagnetic oxides with spinel structure (the S-compounds) the magnetic moment of the various ions can be divided into two groups. The magnetic moments in one group have parallel orientation, but are anti-parallel to the magnetic moments of the other group (cf. [1])). The total magnetic moment is then equal to the difference between the resultant magnetic moments of both groups. This so-called ferrimagnetism has also been found in the compound **M** and likewise occurs in the compounds of the **W**, **Y** and **Z** groups. Just as with the S-compounds, the total magnetic moment depends upon the ions substituted for Me. Measurements have shown that the magnetic moment per gram-molecule of a given **Z**-compound is equal to the sum of the moments per gram-molecule of **M** and the corresponding **Y** compounds. The magnetization can thus be evaluated with the aid of the formula:

$$Z_{11} = M_5 + Y_6,$$

which describes the composition of the Z_{11} blocks. It was further found that the magnetization per gram-molecule of a given **W** compound is in general equal to that of **M** added to the magnetization of two gram-molecules of the corresponding S-material, so that

$$W_7 = M_5 + 2S,$$

which is in agreement with the structure of the W_7 block given above.

It is fortunate that the moments of the blocks composing the unit cells are all parallel and not anti-parallel. Owing to this, the compounds **W**, **Y** and **Z** have saturation magnetizations comparable to those of the ferroxcubes.

Summary. A number of new ferromagnetic materials with interesting properties are described. These materials are compounds of BaO, Fe_2O_3 and MeO, Me representing a divalent ion from the series Mn, Fe, Co, Ni, Zn, Mg. They are prepared by a ceramic process and are related, as regards crystal structure, to ferroxdure. The chemical formulae and the crystal structures are then discussed. The crystal structures are hexagonal and can be described as the close-packing of spheres of oxygen ions, ranged in layers perpendicular to the *c*-axis, in which at certain sites a barium ion is substituted for an oxygen ion. Small metal ions are situated in the interstices between the oxygen ions. A number of "structural units" or "blocks" constitute the elements from which the unit cells of all the new compounds can be built up.

Like ferroxdure, some of these materials show a preferred direction for the magnetization, parallel to the *c*-axis. In other compounds, for which the generic name ferroxplana has been coined, this direction is an "abhorred" direction; here the magnetization has a preferred plane perpendicular to the *c*-axis. Inside this plane the magnetization direction is relatively arbitrary, so that these materials may possess a permeability of approximately 10, about the same as that found — below 100 Mc/s — for the cubic nickel ferrite, ferroxcube 4E. As a consequence of the presence of a preferred plane, the ferromagnetic resonance frequency of ferroxplana lies far higher than that of ferroxcube. These new materials can therefore be used as soft magnetic materials up to a frequency about 5× higher than ferroxcube 4E.

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[12]) L. Néel, Ann. Physique **3**, 137-198, 1948.

A TRANSISTOR RADIO RECEIVER POWERED BY A THERMOPILE

621.396.62:621.375.4:621.362

A problem that has long exercised radio designers is the construction of a receiver capable of reproducing music at normal room volume without requiring any power supply from the mains or from batteries. Even in highly developed areas of the world such as Europe and the U.S.A. many isolated farms and cottages have no electric supply mains, and in less developed areas a mains supply is the exception rather than the rule. Dry batteries as a source of supply are generally rather expensive and have the additional disadvantage of having a limited storage life, particularly in tropical regions. Very few people can afford the luxury of a private generating plant with petrol or diesel engine.

It is not therefore surprising that the *thermopile* has been widely considered as a possible source of supply. The thermopile consists of a series of wires or bars of two dissimilar conductors A and B welded end to end alternately. All the junctions A-B are heated to a temperature T_1 and all junctions B-A are kept at a temperature T_2. The thermo-electromotive force then developed is roughly proportional to the temperature difference $T_1 - T_2$. The e.m.f. per °C temperature difference and per junction is termed the thermoelectric power, a quantity depending on the materials A and B. There is no simple rule for calculating the thermoelectric power, but in general we find a thermoelectric power of some μV/°C for combinations of pure metals, up to some tens of μV/°C for certain alloys and up to some hundreds of μV/°C for some semiconductors.

In the past, the power efficiency of the thermopile was the main consideration, and its usefulness was judged accordingly. This efficiency, however, which is not higher than about 7% at best, may sometimes play only a subordinate part in deciding the usefulness of a thermopile, as is the case here.

Experiments were made some years ago in the Philips Research Laboratories in Eindhoven with thermopiles consisting of a number of thermocouples of easily weldable and non-corrosive alloys (e.g. "Chromel"-"Alumel"). These piles, when heated by a gas flame, produced an e.m.f. of about 2 V, whilst the internal resistance was about 2 Ω. This was sufficient to heat the filaments of the sub-miniature valves with which a radio receiver had been equipped; the anode voltage was obtained by means of a vibrator converting the voltage of 2 V into one of about 100 V. For a consumption of 1 W it was thus possible to attain a volume of sound amply sufficient for an ordinary living-room.

The advent of the transistor has simplified matters considerably. It has no filament and requires a supply of only a few volts, so that a vibrator is no longer necessary. Hence relatively few thermocouples are required for the pile. The pile should preferably be of simple design and unlikely to break down, whilst if it does break down it should be easily repairable by, say, a local radio mechanic or smith. The construction of such a thermopile, made up of a few hundred pieces of wire of not too fine a gauge, then becomes a reasonable proposition.

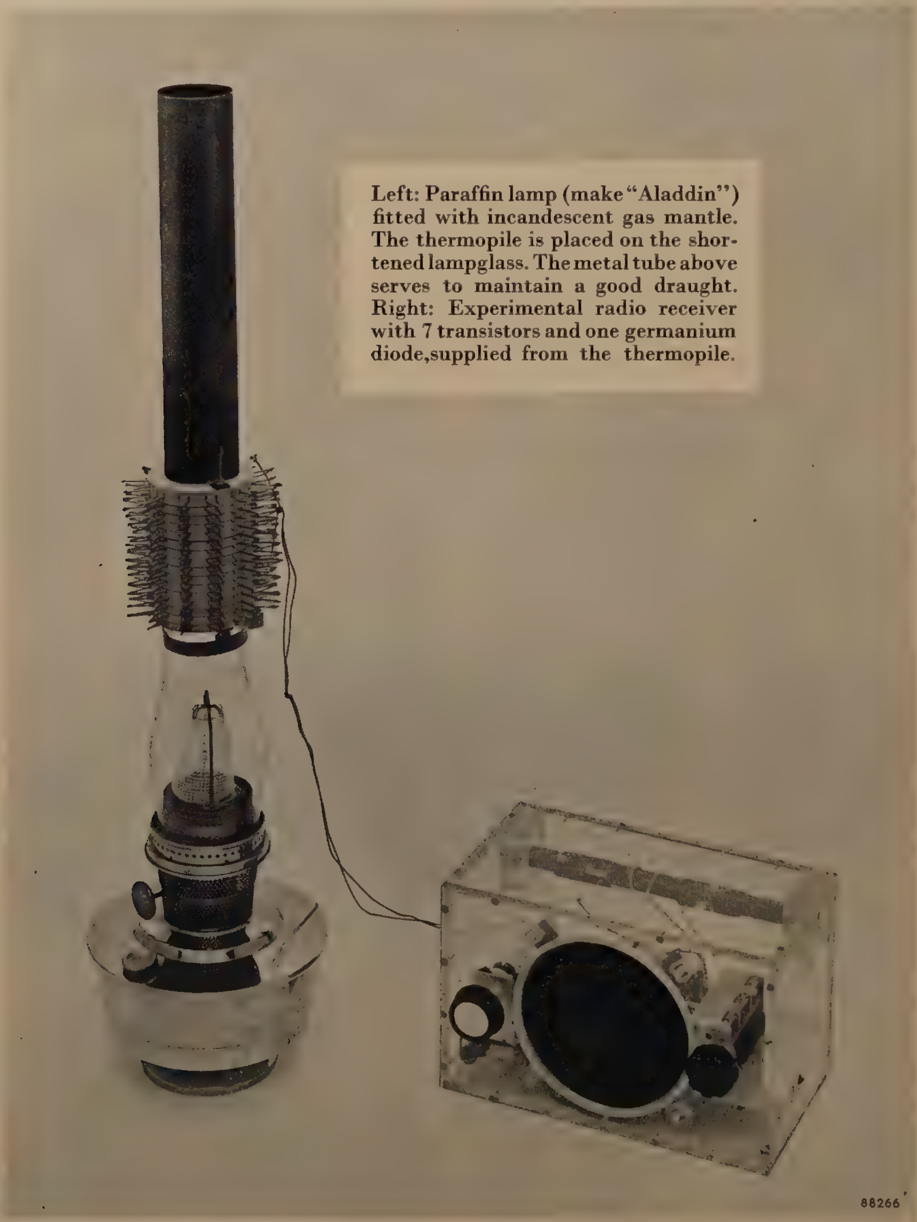
To recapitulate, the problem may be formulated as follows: is it possible to make a satisfactory combination of a cheap heat source, a thermopile, and a radio receiver with transistors and loudspeaker? Laboratory experiments, which will be outlined below, have shown that such a combination is feasible.

The heat source that comes immediately to mind is the paraffin lamp, since this is widely used as a source of light in houses having no electricity or gas supply. Moreover, it is possible, by means of a thermopile, to utilize that part of the heat of a paraffin lamp that is otherwise simply wasted. The present experiments were carried out with a lamp equipped with a Welsbach incandescent mantle. For a consumption of about $\frac{1}{8}$ pint of paraffin per hour this lamp produces an agreeable white light of about 125 candle power; according to present prices in the Netherlands, it works out that the light costs about the same per lumen as that from an electric filament lamp. The special shape of the lamp-glass allows the draught to be regulated so that the vapourized paraffin burns quietly under the mantle, without any formation of soot.

The thermopile has to be adapted to the lamp so as to give good heat transfer but it must not disturb the draught. One of the thermopiles at present being used is made up of "rosettes", units of twelve thermocouples in a radial arrangement. The pile as a whole is a stack of sixteen such rosettes placed on top of the (shortened) lamp-glass (see *figure*). All the thermocouples, numbering less than 200 in all, are connected in series by spot-welds. They consist of "Chromel"-constantan, a combination with a thermoelectric power of about 65 μV per °C temperature difference. The wire is 1.2 mm thick; the internal resistance R_i of the entire pile is 5 Ω. Half the junctions point inwards and are in the stream of hot gases ascending from the chimney; the other half point outwards and are cooled by the surrounding air. When the lamp is burning with a normal flame, the average temperature difference between the hot and the cold junctions is about 180 °C in our model, so that an electromotive force E of about 2.2 V is produced. The power P produced across an external resistance R amounts to

$$P = \frac{R}{R + R_i} \times \frac{E^2}{R + R_i}$$

and is a maximum when $R = R_i$. For $E = 2.2$ V and $R = R_i = 5$ Ω the power is equal to 242 mW. This means that for maximum power consumption the terminal voltage is 1.1 V at a current of 220 mA. This terminal voltage is rather low for transistors which have to drive a loudspeaker. The power produced, on the other hand, is higher than necessary; 100 mW is ample. The terminal voltage then becomes 1.9 V, which is a suitable value.



Left: Paraffin lamp (make "Aladdin") fitted with incandescent gas mantle. The thermopile is placed on the shortened lampglass. The metal tube above serves to maintain a good draught. Right: Experimental radio receiver with 7 transistors and one germanium diode, supplied from the thermopile.

For the sake of simplicity the receiver has been designed as a "straight set", consisting of a single-stage R.F. amplifier with an OC 45 transistor, a detector stage with a germanium diode OA 79 of the point-contact type ¹), and a five-stage A.F. amplifier ²). Four of these five stages comprise an

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¹) Philips tech. Rev. **16**, 225-232, 1954/55.

²) If the supply voltage were 6 V instead of about 2 V, higher collector resistances could be used, which would improve amplification per stage to such an extent that one stage could be omitted.

OC 71 transistor; the output stage employs two OC 72 transistors in push-pull arrangement. In view of the experimental character of the set, A.G.C. has not been incorporated, nor have special provisions been made to compensate for large variations in ambient temperature.

Of the power of 100 mW to be supplied by the thermopile, obviously only a portion is available as A.F. power for the loudspeaker. This portion, however, is larger than might be expected, viz. about 50%. An A.F. power of 50 mW, applied to a sensitive loudspeaker (efficiency about 8%) produces sufficient sound volume for an ordinary room.

For minimum power consumption, with a given audio output power, the output stage is best arranged as a class B push-pull amplifier (i.e. the transistors are just cut off in the absence of a signal). This, however, would involve considerable distortion of weak signals. For this reason an arrangement intermediate between class B and class A was preferred (transistors not entirely cut off in the absence of a signal).

If, between the two bases (input electrodes) of the push-pull output stage, an audio voltage is applied of such amplitude that the transistors operate at full modulation, the collectors (output electrodes) of this stage together pass an average current of about 50 mA. The remainder of the set consumes about 10 mA, so that the total current will be about 60 mA and the terminal voltage 1.9 V. The same applies for normal operation of the receiver on a radio signal with a modulation depth of 100%. Nearly always, however, the modulation depth of the signal is considerably less, with the result that less current is consumed; on the average this is only 40 mA.

If no special provisions were made, the fairly high internal resistance of the thermopile would give rise to feedback, since this resistance would be common to all stages; the receiver would therefore be liable to oscillation (at a frequency of a few c/s). To prevent this, two measures have to be taken:

1) the coupling between the various stages via the common supply source has to be reduced, e.g. by shunting the thermopile with a large capacitance;
2) the amplification for very low frequencies has to be reduced by employing a coupling capacitor of low capacitance in one of the stages.

An inductive aerial of the "Ferroceptor" type [3]), i.e. a coil wound on a ferroxcube rod acting as a frame aerial, is used. In the present case the rod is 200 mm long and 15 mm thick, the coil has a self-inductance $L = 185$ μH (a value suitable for medium waves), the effective height [4]) $h = 12$ mm and the Q, without load, is 160. The receiver produces its maximum output power with a signal of field strength $F = 1$ mV/m and having a modulation depth of 30%.

If the aerial is matched to a resistance R_a, it produces in this resistance a power $P_a = (QFh)^2/4R_a$. Writing $R_a = 2\pi f LQ$, f being the frequency of the incoming radio signal, we find, for $f = 10^6$ c/s, $P_a = 5 \times 10^{-12}$ W. To obtain an output power of 50 mW we must effect a total amplification of $50 \times 10^{-3}/5 \times 10^{-12} = 10^{10}$ times, i.e. 100 dB. Assuming a modulation depth of 30% and in view of the fact that the efficiency of the detector stage is considerably below 100%, the overall amplification should in fact amount to about 125 dB. The receiver described here gives just this amplification.

A common touchstone for the quality of reproduction of a receiver is the R.F. and I.F. bandwidth. As a measure of this we may take the difference between the two frequencies at which the amplification has fallen to 1/1.6 of its value at the resonance frequency.

In this receiver the bandwidth so measured is 4.25 kc/s. The attenuation on detuning by 9 kc/s (i.e. the frequency separation between broadcasting transmitters in the medium wave range) amounts to a factor of 8. This figure is fairly low in comparison with that of ordinary radio receivers, but could only be improved by employing more complicated circuitry. In general, however, it will suffice for interference-free reception of powerful and not too distant transmitters, which was the purpose we had in mind when developing this experimental receiver.

J. van HENGEL and J. VOLGER

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[3]) H. Blok and J. J. Rietveld, Philips tech. Rev. **16**, 186-188 and 191-193, 1954/55.

[4]) See the article quoted in [3]), 190 and 193.

THE APPLICATION OF FERROXCUBE IN UNIDIRECTIONAL WAVEGUIDES AND ITS BEARING ON THE PRINCIPLE OF RECIPROCITY

by H. G. BELJERS.

621.372.852.223:621.318.134:538.566.5

Until recently, the application of ferroxcube was limited to high frequency cores or other magnetic circuits, up to frequencies (10 to 100 Mc/s) at which the losses became appreciable. It has been found, however, that even at much higher frequencies (1000 to 30 000 Mc/s), where the magnetic losses may be very great, there are important possibilities of application, especially for magnetically polarized ferrites, such as ferroxdure and magnetized ferroxcube. In this article, the theory and practice of such applications will be examined more closely.

The principle of reciprocity

The principle of reciprocity 1) is manifested in many branches of physics, such as, for example, mechanics, optics and electricity. It may be formulated as follows: if a cause X, acting on a point A of a system, brings about an effect x at a point B, then the same cause X, acting on B, will give rise to the same effect x at A.

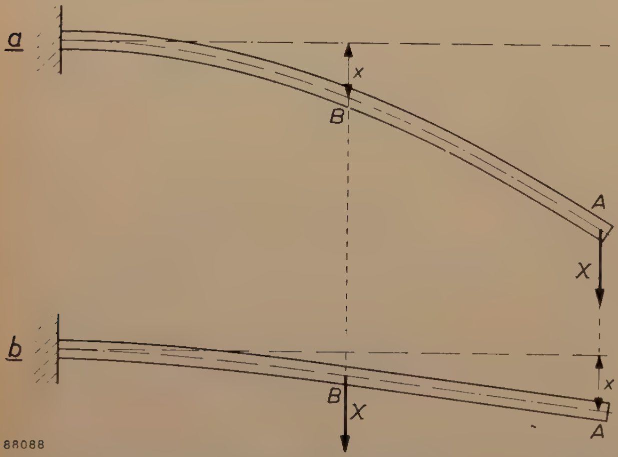

Fig. 1. A horizontal rod clamped at one end, as an example of the principle of reciprocity in elasticity. A force X at A causes a displacement x at B. The same force X at B causes an identical displacement x at A.

Fig. 1 illustrates a simple example from elasticity. A rod clamped at one end in a horizontal position, is loaded at its other end with a weight X, as a result of which point B is given a vertical displacement x. If the same weight X acts at B, then A will likewise be displaced through a distance x (notwithstanding the fact that the shape of the bent rod differs in the two cases).

An electrical example is furnished by a linear network (composed of resistances, capacitances and inductances). If, in such a system, an electromotive force X, acting in a branch A of the network causes a current x in a branch B, the e.m.f. X acting in branch B will give rise to the same current x in branch A; this is true not only for direct voltages and currents, but also for alternating voltages and currents: in the latter case the currents x in A and B will not only be of the same amplitude — they will also have the same phase.

The principle of reciprocity has been used in studying the propagation of electromagnetic waves, e.g. for determining the most suitable site for a radio transmitter. Instead of setting up a fixed receiver at a point B and varying the position A of the test transmitter, it was merely necessary to have a fixed transmitter at B, whose reception was measured at a variable point A. This was obviously a quicker and more economical procedure.

A simple optical example of reciprocity is the fact that when a luminous flux of intensity I impinges on a plane-parallel plate, the latter transmits a flux of aI, irrespective of which is the incident side of the plate.

There are, however, exceptions to reciprocity. In mechanics an example is provided by the behaviour of a gyroscope (*fig. 2*). Imagine the latter, viewed from z, to be rotating in the positive direction (clockwise). A couple, acting clockwise about the x-axis for a time t will cause the axis of rotation of the top to turn about the y-axis (i.e. in the x,z plane) through an angle ϑ, in the *negative* direction, viewed from y. A positive couple of like magnitude, acting for a time t about the y-axis causes a turning of the top's axis about the x-axis (in the y,z plane) through the same angle ϑ, but in a *positive* direction, viewed from x. The magnitude of the effect is in either case the same, but its sign is different.

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1) Propounded by Helmholtz in J. Math. **56**, 29, 1859; formulated for mechanics by E. Betti, Nuovo Cimento 1872. See also Rayleigh, Proc. London Math. Soc. **4**, 357-368, 1873; Sci. Papers I, pp. 170-181 and Enz. Math. Wiss., IV (4), p. 86, note.

An optical example, in which the principle of reciprocity does not apply, is Rayleigh's well-known experiment. [2]) This is shown diagrammatically in *fig. 3*. At A there is a polarizer (Nicol prism or polaroid sheet) mounted with its direction of polarization vertical; at B there is a similar polarizer, whose direction of polarization, viewed from A, is positioned 45° clockwise with respect to A. Between A and B there is a solenoid C, which sets up a magnetic field. In the field is a transparent rod (or column of liquid) of a substance which shows the phenomenon of magnetic rotation of the plane of polarization (Faraday effect). For diamagnetic substances this rotation is "positive", i.e. regardless of the direction of propagation, it is in the same sense as the current producing the magnetic field. (With paramagnetic substances, there is both a paramagnetic and a diamagnetic contribution, which are usually opposite in sign). The nature of the substance, the direction of the current, the length of the coil and the strength of the field are so chosen in the experiment, that for light propagated from A to B, the rotation is clockwise and amounts to 45°. An incident beam of light from the left is therefore polarized at A and, on arriving at B, passes through completely. On the other hand an incident beam coming from right will be polarized by B and its direction of polarization will then be rotated anticlockwise through 45° and will thus be perpendicular to the polarizing direction of A. Such a beam will be completely blocked by A. The system will transmit light in the AB direction, but not in the BA direction. On the other hand this non-reciprocity would not be observed if there were a naturally rotating substance (quartz, sugar solution) between the two polarizers instead of a magnetically rotating substance. In this case, if the rotation from A to B were clockwise, that from B to A would also be clockwise and the light would be transmitted in both directions.

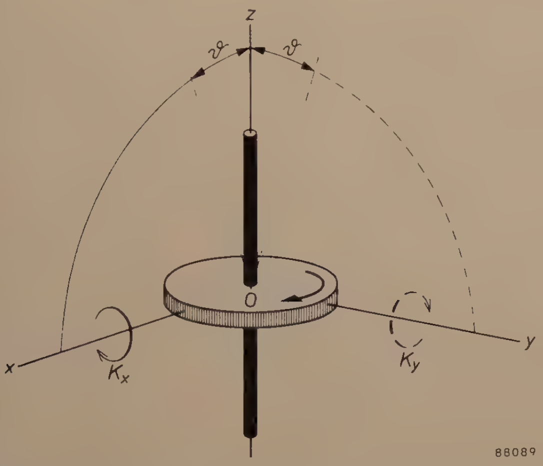

Fig. 2. A gyroscope as an example from mechanics in which the principle of reciprocity is not complied with. A couple K_x acting about the x-axis, causes the axis of the gyroscope to incline in the x-z plane. The angle ϑ is proportional to the product of K_x and the time t for which the couple acts. Viewed from y, the axis of the top inclines to the *left*. A couple of the same magnitude and the same sense acting about the y-axis causes the axis of the gyroscope to incline in the y-z plane through an angle ϑ: viewed from x the inclination is to the *right*.

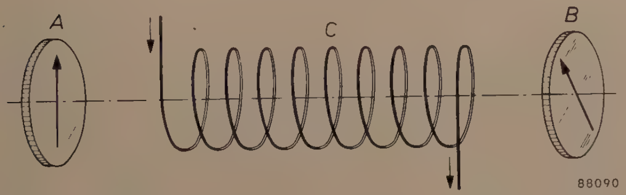

Fig. 3. Rayleigh's experiment, an optical example in which the principle of reciprocity is not obeyed. A and B are polarizers (e.g. Nicol prisms). Viewed from A, B is oriented 45° clockwise with respect to A. C is a coil containing a diamagnetic material (with a positive Faraday effect); the plane of polarization of a beam of light passing through this material is always rotated in the direction of the current producing the magnetic field. The system allows a beam of light to pass from left to right but not in the reverse direction.

Likewise in the propagation of radio waves the principle of reciprocity may be found not to apply, again in those cases in which there is magnetic rotation of the plane of polarization. The above-mentioned reciprocity of radio transmitter and receiver, for example, no longer obtains if reception is principally afforded by reflections at the Heaviside layer, and there is a noticeable rotation of the plane of polarization, brought about by the earth's magnetic field.

If it is required to construct a linear electric network that does not comply with the principle of reciprocity, it is necessary to incorporate in it the non-reciprocal network element, which Tellegen [3]) has called a *gyrator*, or a component whose equivalent circuit contains a gyrator, in addition to reciprocal elements, such as resistances, inductances and capacitances.

Such non-reciprocal components can actually be made for use with microwaves, one of the effects employed in their construction being magnetic rotation of the plane of polarization. Non-reciprocal components of this kind are made possible by the existence of ceramic ferromagnetic materials, which owing to their low conductivity are transparent to electromagnetic waves in the microwave region. Ferroxcube is such a material.

At first, ferroxcube was mainly employed for coil cores for use in the region below 10—100

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[2]) Rayleigh, Phil. Trans. **176**, 343-366, 1885; Sci. Papers II, 360-383.

[3]) B. D. H. Tellegen, The gyrator, an electric network element, Philips tech. Rev. **18**, 120-124, 1956/57 (No. 4/5).

Mc/s, as the magnetic losses are low in this range of frequencies. In the microwave range (1000—30 000 Mc/s), in which unpolarized ferroxcube gives appreciable losses, waveguides can be constructed using magnetically polarized ferroxcube which function as non-reciprocal elements. The lower limit of frequency is then determined by the minimum magnetic field required for magnetic saturation, the upper limit by the maximum magnetic field that can in practice be produced in a waveguide.

The non-reciprocal behaviour of such elements manifests itself in the fact that the attenuation is different in opposite directions. This is of direct practical importance in microwave technique. Such elements (directional isolators, "unilines") are already being applied on a considerable scale and frequent articles on them appear in the literature [4]).

In the following, a few examples of unidirectional waveguides of this type will be described, but there will first be a brief exposition of the phenomenon of gyromagnetic resonance, the working principle of such waveguides. For those interested, the theory is treated somewhat more fully in an appendix at the end of this article.

Gyromagnetic resonance

The mechanical example of non-reciprocity given above was that of a gyroscope. In actual fact, the gyroscopic effect is involved in the other examples, too, for electrons, owing to their orbital and their spin, show a similar behaviour. More especially, the applications of ferroxcube mentioned above are based upon the phenomenon of gyromagnetic resonance which was predicted in 1935 by Landau and Lifshitz and has been discussed in this Review [5]). Landau and Lifshitz demonstrated that a spinning electron, oriented by a magnetic field H executes a free precession about the direction of this field, with angular velocity

$$\omega_{\mathrm{p}} = \gamma H, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where [6])

$$\gamma = 2.21 \times 10^5 \ \mathrm{m/A.sec.} \quad . \quad . \quad . \quad . \quad (2)$$

The direction of rotation of the precession is the same as that of a current which would produce the field H. An alternating magnetic field, perpendicular to H, gives rise to a forced precession with the same direction of rotation as the free precession and with the angular frequency ω of the alternating field. If ω differs little from ω_{p}, resonance occurs and the precession becomes very large.

What has been said above holds primarily for a free electron, but *mutatis mutandis* it also applies to an electron in a ferromagnetic crystal. In a crystal the free precession is damped and the forced precession is attended with losses, which become particularly great when $\omega \approx \omega_{\mathrm{p}}$. Further, the value of ω_{p} is in general no longer determined by the simple formula (1): it depends in a more complex manner upon the magnetic state of the material. For an ellipsoid of ferroxcube with one of its axes parallel to the external field H_{e} (z direction), ω_{p} follows from Kittel's formula (see articles I and II, footnote [5])):

$$\omega_{\mathrm{p}} = \gamma \sqrt{[H_{\mathrm{e}} + (N_x - N_z)M_{\mathrm{s}}]\ [H_{\mathrm{e}} + (N_y - N_z)M_{\mathrm{s}}]}\,, \quad . \quad . \quad . \quad (3)$$

where M_{s} is the saturation magnetization and N_x, N_y and N_z the demagnetization factors ($N_x + N_y + N_z = 1$).

In view of what is to follow, it is useful to regard the alternating magnetic field, which is applied perpendicularly to H_{e} and causes the forced precession, as a superposition of two opposing "rotating fields" (each of which may be represented as a vector that rotates in a plane perpendicular to H_{e}). Only the field that rotates in the same direction as the free precession, leads to resonance and its associated losses. The opposing rotating field has scarcely any effect on the spins.

A direct consequence of this is that the Faraday effect can be observed with plane polarized magnetic waves propagated in the ferroxcube in the direction of the magnetizing field H_{e}. The resolution of the alternating magnetic field of the wave into two opposing rotating fields gives rise to two circularly opposed polarized waves. On account of the difference mentioned above in their interaction with the spins, these waves have different rates of propagation.

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[4]) C. L. Hogan, Ferromagnetic Faraday effect, Bell Syst. tech. J. **31**, 1-31, 1952. A. G. Fox, S. E. Miller and M. T. Weiss, Behaviour and applications of ferrites in the microwave region, Bell Syst. tech. J. **34**, 5-103, 1955.

[5]) H. G. Beljers and J. L. Snoek, Gyromagnetic phenomena in ferrites, Philips tech. Rev. **11**, 313-322, 1949/50 hereafter to be referred to as I; H. G. Beljers, Amplitude modulation of centimetre waves by means of ferroxcube, Philips tech. Rev. **18**, 82-86, 1956/57, hereafter to be referred to as II.

[6]) For γ we have the relationship

$$\gamma = g \frac{|e|}{2m_0} \mu_0.$$

Here, $|e|$ is the absolute value of the charge on the electron (1.6×10^{-19} coulomb), m_0, its rest mass (0.9×10^{-30} kg), $\mu_0 = 4\pi \times 10^{-7}$ Vs/Am and g the Landé factor. For a free electron the value of the latter is approximately 2, for an electron bound in a ferromagnetic crystal lattice, its value may vary somewhat, viz. from 2.00 to 2.25, owing to a correction for the orbital field.
In the literature the symbol is sometimes used for the negative quantity $g\,(e/2m_0)\,\mu_0 = -g\,(|e|/2m_0)\mu_0$.

Owing to the phase difference between the two circular components, which this brings about, the plane polarized wave displays a rotation of its plane of polarization which is proportional to the distance covered in the ferroxcube.

Non-reciprocal elements employing Faraday rotation

For the transmission of microwaves rectangular waveguides are normally used, in which the long side a of their cross-section satisfies: $a < \lambda < 2a$. The propagation in the waveguide is then brought about by a wave whose mode of vibration is designated TE_{10}, the electric vector being parallel to the short side of the rectangle (see *fig. 4a*).

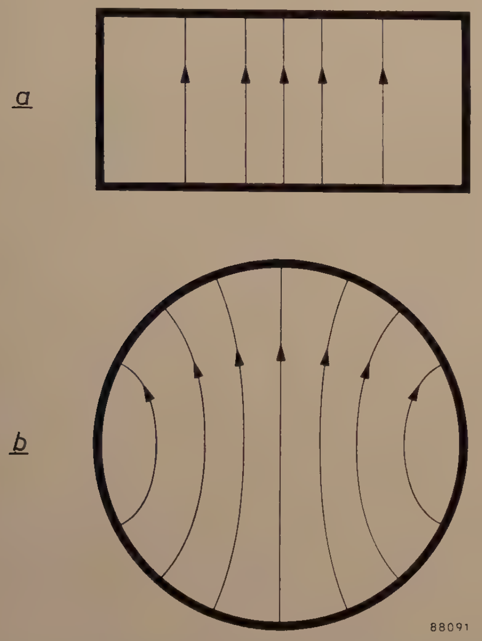

Fig. 4. *a*) Rectangular waveguide with mode of vibration TE_{10}; *b*) Circular waveguide with mode of vibration TE_{11}. The electric lines of force are indicated in both cases.

For an element with rotation of the plane of polarization it is customary to employ a circular waveguide with propagation in the TE_{11} mode (fig. 4*b*). The ferroxcube usually takes the form of a thin cylindrical rod mounted coaxially in the waveguide and magnetized along its axis (if the waveguide were to be completely filled with ferroxcube, a large number of modes of vibration could occur simultaneously, and this would lead to undesirable effects, especially with long rods). An example of the rotation obtained with the above-described arrangements at a frequency of 24 000 Mc/s, as a function of the axial magnetic field may be seen in *fig. 5*. The angle of rotation increases with the increasing strength of the magnetic field, until saturation is reached.

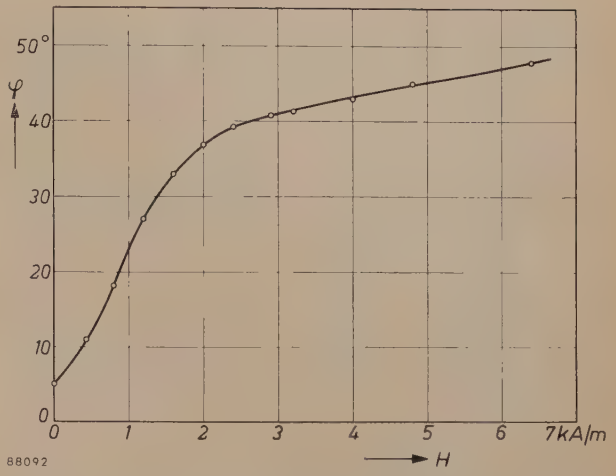

Fig. 5. The rotation φ of the plane of polarization of an electromagnetic wave at the end of a circular waveguide fitted with an axial rod of magnetized ferroxcube (length 4.4 cm), as a function of the strength H of the magnetizing field.

The essential condition now is that the sign of the rotation should depend upon the direction of the magnetic field with respect to the direction of propagation. The circular waveguide, provided with a ferroxcube rod, can be incorporated in a system of rectangular waveguides (see *fig. 6*) with the aid of adapters (the cross-sections of which change gradually from rectangular to round to avoid reflection). If the adapters at either end are at 45° with respect to each other, and if the Faraday rotation is also set at 45°, the wave will be transmitted almost completely in one direction. In the reverse direction the wave cannot travel further after rotation, since the electric vector is now parallel to the long side of the rectangular section, which does not represent a possible mode of vibration. It can be arranged that the energy is not reflected, but absorbed on the spot, by mounting a thin plate of a semi-conductor e.g. graphite-containing "Philite", parallel to the electrical lines of force.

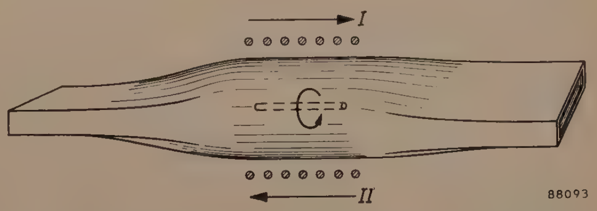

Fig. 6. Construction of a directional isolator, based on the Faraday effect. If the magnetic field be applied in the direction *I*, a wave can then be propagated through the waveguide only in that direction.

Such a system is a directional isolator, because if it be interposed between two equipments A and B, $A \rightarrow B$ being the desired direction of transmission, it will prevent any waves that might be reflected at B from returning to A; A is thus "isolated" from these undesirable waves from *B*. Since the Faraday rotation depends upon the frequency, the element can be employed only in a limited range of frequencies (for a given magnetic field). *Fig. 7* gives the measured values of the attenuation in both directions in the frequency range 23 600—24 500 Mc/s for such a directional isolator constructed in this laboratory.

The polarizing magnetic field at the axis of this isolator is about 5000 A/m (60 Oe). It is produced by a few rings of axially magnetized ferroxdure 7), which can be slipped round the waveguide. Some measure of control can be exercised over the strength of the field by moving the rings along the waveguide and the angle of rotaton can thus be adjusted to the correct value. Instead of a ferroxcube rod, a rod of ferroxdure, magnetized along its longitudinal axis can be mounted coaxially in the waveguide. An external magnetic field is then unnecessary. Care must be taken when using this directional isolator to avoid working under such conditions that the circular component, which has the same direction of rotation as the spin precession, is too strongly damped. This would give rise to inequality of the two circular components, and hence would diminish the attenuation action. This is equivalent to saying that the wave frequency should not approximate too closely to the resonance frequency ω_p. The axial magnetic field must not, therefore, be given too high a value. A strong field is in fact not required to magnetize a thin rod.

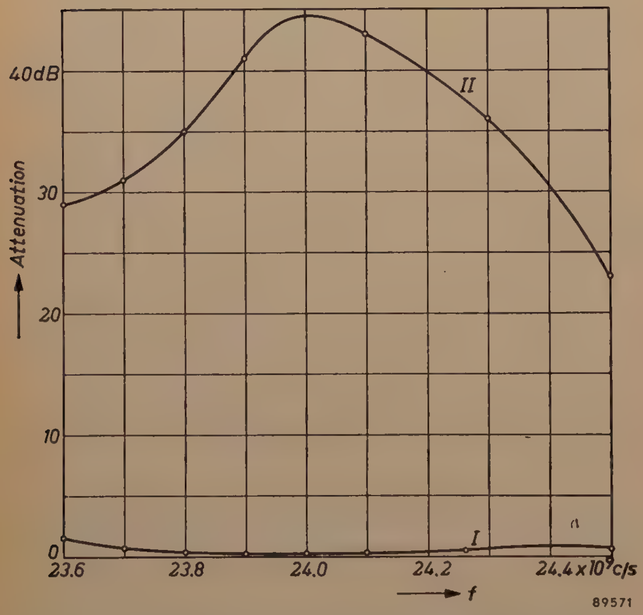

Fig. 7. Attenuation brought about by a directional isolator of the type shown in fig. 6, as a function of the frequency *f*, in the frequency range 23 600—24 500 Mc/s. Curve I is for the forward direction in which the wave is transmitted, curve II for the reverse direction in which the wave is suppressed.

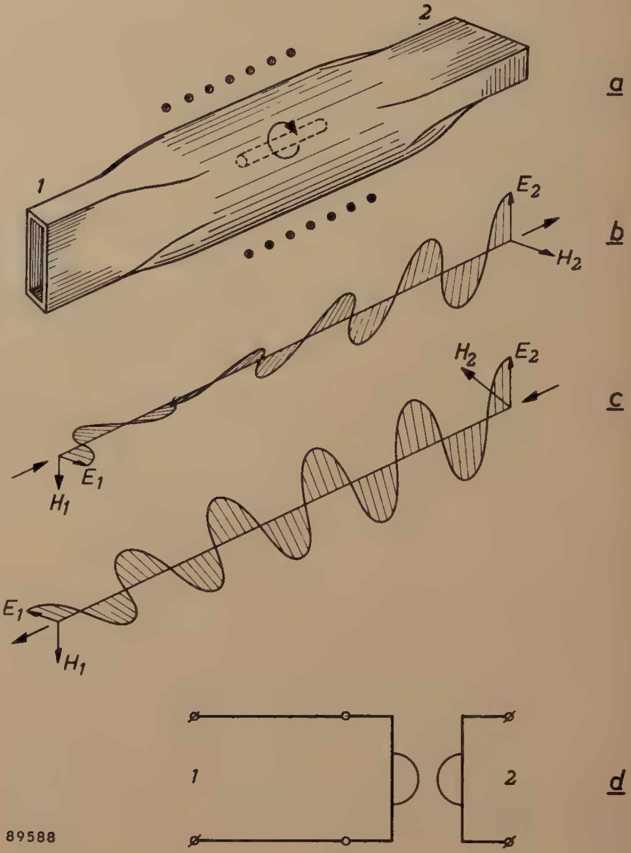

Fig. 8. *a*) Waveguide showing a difference in transmission length of $\lambda/2$ in the two directions (after Hogan, loc. cit. 4)).
b) Instantaneous view of wave propagated in one direction.
c) Instantaneous view of wave propagated in the opposite direction to (*b*).
d) Equivalent circuit of the waveguide, comprising a Lecher line and an ideal gyrator 8).
The waveguide shown can be seen to possess the properties of a gyrator from the relationship between the electric vector E of the incident wave and the magnetic vector H of the emergent wave. In the one case (*b*) we have $H_2 = E_1/Z$, whilst in the other case (*c*) $H_1 = -E_2/Z$, Z representing the characteristic impedance. These relations (or their transmission line equivalents, $i_2 = v_1/Z$ and $i_1 = -v_2/Z$) may be compared with the formulae for the gyrator (see eq. (9) in the article cited in note 3)).

Such an element can also be arranged to give a rotation of 90° instead of 45°. This will result in equal transmission in both directions: the non-reciprocal behaviour then manifests itself in the fact that the phase differs by 180° for the two directions. Such an element is an "ideal gyrator" as postulated by Tellegen. This is illustrated in *fig. 8*.

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7) See Philips tech. Rev. **14**, 194-208, 1952/53.

8) For equivalent circuits of other unidirectional waveguides, see H. J. Carlin, Principles of gyrator networks, Proc. Symp. Mod. Adv. Microwave Techn. New York 1954, p. 175.

Non-reciprocal elements with transverse magnetic fields

Propagation in a transverse magnetic field can also be made use of in the construction of non-reciprocal elements. Here a normal rectangular waveguide (see fig. 4*a*) is used, in which the propagation is in the TE_{10} mode. Consider a system of coordinates with the z-axis parallel to the short side of the rectangle, and the x-axis parallel to the long side of the rectangle; the y-axis then coincides with the longitudinal axis of the waveguide, i.e. the direction of propagation. The electrical lines of force are parallel to the z axis; the magnetic lines of force are closed loops in the x,y plane as shown in *fig. 9a* [9]).

The magnetic field has components:

$$\left.\begin{aligned} h_x &= j\beta A \cos(\pi x/a) \exp[j(\omega t - \beta y)] \,, \\ h_y &= (\pi/a) A \sin(\pi x/a) \exp[j(\omega t - \beta y)] \,, \\ h_z &= 0. \end{aligned}\right\} \quad . \quad . \quad (4)$$

where A is an arbitrary constant, a the length of the longer side of the waveguide and β the propagation constant in the waveguide ($\beta = 2\pi/\lambda_g$). Considering a point x,y we see that the magnitude and direction of the magnetic vector at that point vary periodically. For certain values of x, however, the nature of this variation is such, that only the direction of the magnetic field changes and not its strength, so that the magnetic vector describes a circle and a local rotating field is set up. This is the case for those values of x, for which $h_x = \pm j h_y$ (equal amplitude, phase difference 90°) or:

$$\tan\frac{\pi x}{a} = \pm\frac{\beta a}{\pi} = \pm\frac{2a}{\lambda_g} . \quad . \quad . \quad . \quad (5)$$

Two values are found, $\pm x_1$, on either side of the centre. For one of these values, the rotation of the magnetic vector, viewed along z, is positive, for the other negative. Both rotations change sign as the direction of propagation changes sign.

If, now, a thin plate of ferroxcube be mounted in the waveguide at x_1, and a constant magnetic field H be applied in the z-direction, i.e. across the direction of propagation of the wave, the situation is the same as that described earlier (page 160): a rotating magnetic field h perpendicular to the constant field H. For that direction of propagation in the waveguide for which the direction of rotation of h in the ferroxcube plate is the same as that of the spin precession around H, gyromagnetic resonance can occur, with corresponding damping of the wave. A wave with the reverse direction of propagation passes through almost unimpeded.

Unlike the previous case (Faraday effect), in which the damping must remain small, it is precisely on the damping in the material that the working principle is based, and the damping must therefore be made as great as possible. This means that ω must lie close to ω_p. Although the presence of the plate, which has a fairly high dielectric constant ($\varepsilon_r = 10$) and sometimes also a fairly high permeability, strongly distorts the original field, it is nevertheless possible to mount the plate in such a way that the wave whose magnetic vector in the plate rotates in the opposite sense to the spin precession passes through almost unattenuated.

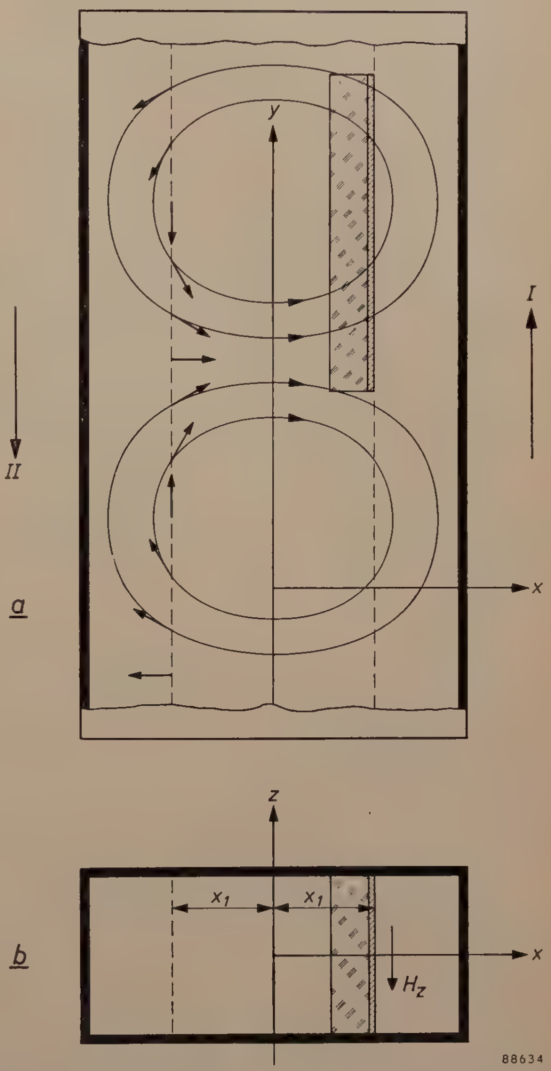

Fig. 9. The magnetic lines of force in a rectangular waveguide with mode of vibration TE_{10}. At points at a certain distance x_1, on either side of the axis, the magnetic vectors are equal and constant in magnitude and rotate uniformly.
b) Section of the waveguide. By mounting a ferroxcube plate magnetized in the z-direction (across the direction of propagation) in the yz plane and distant x_1 from the axis, gyromagnetic resonance is set up in the plate and the wave is therefore attenuated in direction *II*.

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[9]) M. L. Kales, H. N. Chait and N. G. Sakiotes, J. appl. Phys. **24**, 816-817, 1953.

On closer examination it is found that the correct position for the plate is not exactly at x_1, since then the purely circular polarization of the magnetic vector occurs in the space outside the plate but not in the ferrite material itself, owing to the demagnetization in the plate. The plate must therefore be shifted somewhat nearer to the centre of the waveguide [10]). The resonance frequency can be most simply derived from Kittel's formula (3), by substituting the values $N_z = N_y = 0$ and $N_x = 1$, which hold for a thin plate. We then have (if B_z is the induction in the z-direction):

$$\omega_p = \gamma \sqrt{H_z B_z / \mu_0} \, . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This formula turns out to be valid even when the dimensions of the plate in the y and z directions are no longer small compared with the wavelength in the material, as was assumed in deriving (3). Since the plate has approximately, though not exactly the form of an ellipsoid, M does not have the same value or direction in all parts of the plate. For this and a number of other reasons, such as magnetic anisotropy in the crystals, porosity and internal stresses, the value of ω_p in the material is not accurately determined, and there is no sharp resonance. This is to be regarded as an advantage, as it leaves a certain freedom in the frequency, and one-way transmission systems so constructed can be used for a fairly wide range of frequencies.

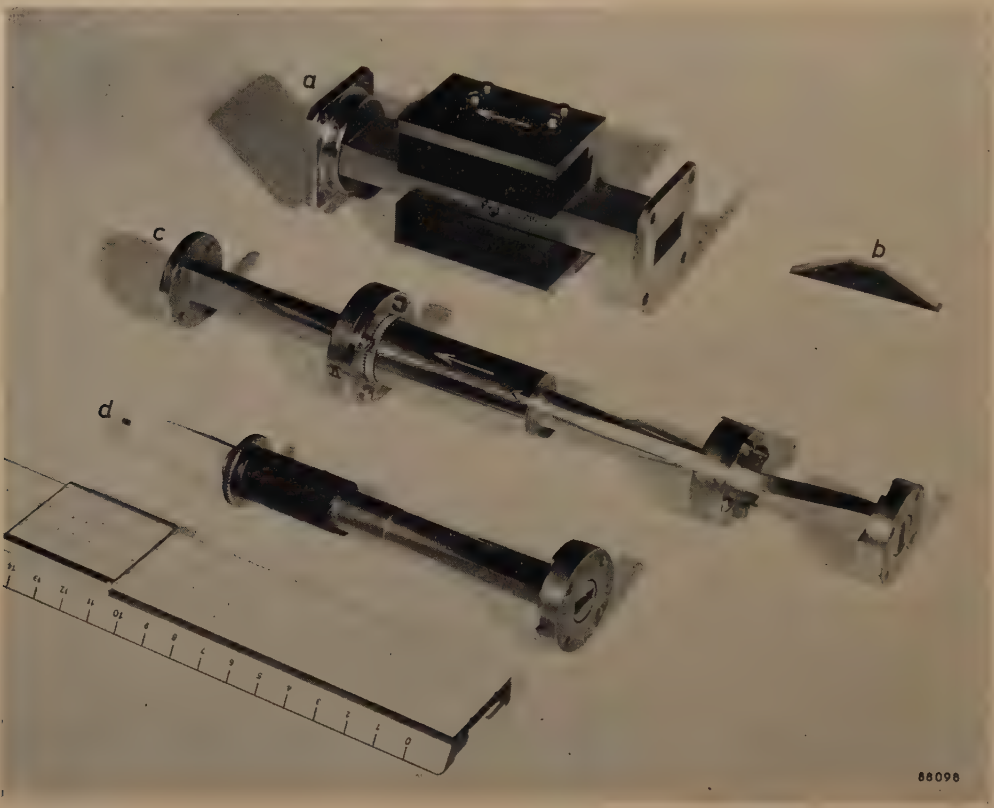

Fig. 10. *a* directional isolator, of the type shown in fig. 9, for the frequency region of 9500 Mc/s; two blocks of ferroxdure II with a soft iron yoke produce the transverse magnetic field; the arrow shows the forward direction; *b* ferroxcube plate on silica mount used in *a*. *c* directional isolator for the frequency region of 24 000 Mc/s, which makes use of Faraday rotation. *d* detail of *c*, with the ferroxcube rod pushed out on the left; the ferroxcube is enclosed in a white cylinder of foamed polystyrene for centering; to the right of the milled ring are the three axially magnetized rings of ferroxdure which produce the axial magnetic field.

We may conclude with some data on a directional isolator constructed on the above principle for the frequency range 8500—10 000 Mc/s (see *a* in *fig. 10*)

The ferroxcube plate (Ni-Zn ferrite, on a silica mount,) is made in the form of a trapezium (*b* in fig. 10) in order to reduce reflection at the plate to a minimum. For low reflection the difference in length between the long and short sides of the trapezium must be about one wavelength. It has also come to light that the dielectric effect of the silica (the losses from which are negligible) results in a certain distribution of the energy of the wave over the section of the waveguide, which appreciably enhances the quality of the isolator: the attenuation in the reverse direction is considerably increased, that in the forward direction being unaffected. The transmission in both directions is given in the graph in *fig. 11* as a function of the frequency.

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[10]) More exact calculation shows that h_x/jh_y should be put equal to $\sqrt{B/\mu_0 H}$ instead of to unity.

As has already been remarked, it is necessary to work with a resonance frequency ω close to ω_p in order to obtain satisfactory attenuation of the wave. The polarizing magnetic field must therefore be stronger than in the directional isolator based on the magnetic rotation of the plane of polarization. An external system of magnets, comprising two blocks of ferroxdure II, 16 mm in height, with a soft iron yoke, produces in the waveguide a transverse magnetic field of about 142 000 A/m (1780 Oe). This is found to be in agreement with formula (6) if it is assumed that $g = 2.10$ (see note [6]); thus $\gamma = 0.232$ Mc/s per A/m and $\mu_0 M_s = 0.4$ Wb/m². Fine adjustment of the field strength is provided for by introducing an air gap in the yoke which can be closed with a bridge.

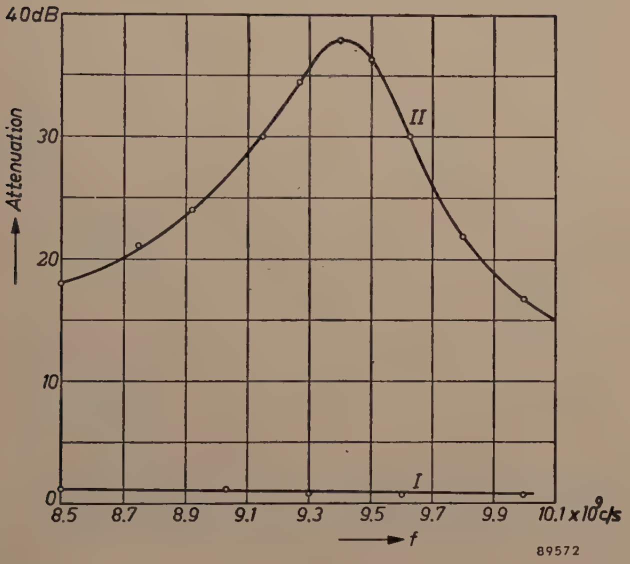

Fig. 11. Attenuation in both directions by the directional isolator *a* in fig. 10, as a function of the frequency, in the frequency range 8500—10 000 Mc/s.

Longer waves require a weaker magnetic field. *Fig. 12* shows a similar directional isolator for the frequency range 3800—4200 Mc/s. The ferroxdure magnet has practically the same dimensions as that in *a*, fig. 10, while the width of the air gap, which is dictated by the dimensions of the waveguide, is roughly twice that in *a*.

For still longer waves the magnetic field to be applied is so weak that the ferroxcube plate can no longer be saturated. This determines the lower limit of frequency, for which directional isolators working on this principle can be realized.

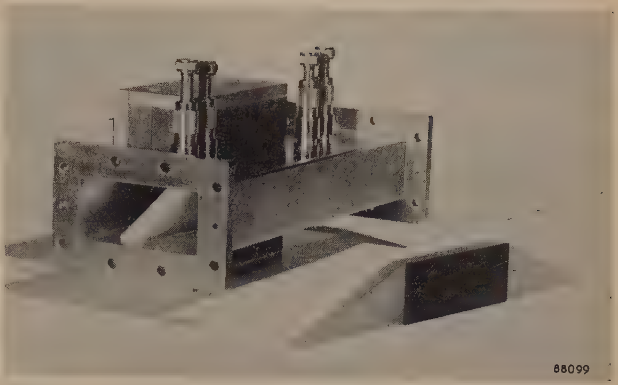

Fig. 12. Directional isolator for the frequency region of 4000 Mc/s. In the foreground is the silica mount with the ferroxcube plate attached to it. The height is 22 mm.

Appendix: Essentials of the theory governing the above phenomena

For a more quantitative insight into the phenomena discussed above, we shall now give the mathematical treatment for a special case: that in which a plane-polarized wave is propagated without damping in the direction of magnetization in an infinite, magnetized medium.

Complete theoretical treatment of the directional isolators described is scarcely possible. In the first place the field in a waveguide is far more complex than in the case of a plane wave: it can be regarded as a superposition of plane waves whose direction, amplitude and phase are such that the boundary conditions are satisfied [11]). Further, in a directional isolator the waveguide is only partly filled with the ferromagnetic material. The field within the material differs from that outside, and both fields must together conform to the boundary conditions [12]). Finally, for a full treatment the damping must be taken into consideration; it is always present and in fact essential with the second type of directional isolator. Obviously the situation is a complex one.

For the limited aim that we have in view, we shall introduce a system of coordinates x, y and z, with the z-axis in the direction of the magnetic field (H_z). Let us suppose that the ferromagnetic medium is magnetized to saturation, in the z-direction (magnetization M_s). We then have:

$$\frac{1}{\mu_0} B_z = H_z + M_s .$$

The behaviour of the medium when an alternating magnetic field is applied to it, is expressed by certain relationships [13]) between the components b_x, b_y, b_z of the alternating induction and the components h_x, h_y, h_z of the alternating field in the material. These relationships are.

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[11]) See, e.g. W. Opechowski, Electromagnetic waves in waveguides Philips tech. Rev. **10**, 13-25, 46-54, 1948.

[12]) For further details, see: A. A. T. M. van Trier, Guided electromagnetic waves in anisotropic media, Dissertation, Delft 1953; also Appl. sci. Res. **133**, 309-371, 1953.

[13]) The equations (in which damping is neglected) were derived from the equations of motion for an individual spinning electron; see D. Polder, On the theory of ferromagnetic resonance, Phil. Mag. **40**, 99-115, 1949. For the complete formulae (with damping), see, for example, C. L. Hogan, loc. cit.[4]).

$$\left.\begin{aligned}\frac{1}{\mu_0}b_x &= ph_x + \mathrm{j}qh_y,\\ \frac{1}{\mu_0}b_y &= -\mathrm{j}qh_x + ph_y,\\ \frac{1}{\mu_0}b_z &= h_z,\end{aligned}\right\} \quad \dots\dots\dots \quad (7)$$

where p and q represent:

$$\mu = 1 + \frac{\gamma^2 H_z M_s}{\gamma^2 H_z^2 - \omega^2}, \qquad q = \frac{\omega\gamma M_s}{\gamma^2 H_z^2 - \omega^2}. \quad \dots \quad (7a)$$

In order to investigate the propagation of an electromagnetic wave in this medium, we must write down Maxwell's equations and substitute the expressions in (7) above for the components of B. This has been worked out generally by Polder [13]. For a plane wave without absorption, such as we shall confine ourselves to here, the periodic electric field and the periodic magnetic field are at right angles to each other and in phase, so that we need only examine the magnetic field. The plane-polarized wave of amplitude $\hat{h}$ advancing in the z-direction, can be resolved into two opposing circularly polarized components with the rates of propagation v_+ and v_-:

$$\left.\begin{aligned}+\ \text{component:} &\begin{cases} h_x = \phantom{-\mathrm{j}}\dfrac{\hat{h}}{2}\,e^{\mathrm{j}\omega(t-z/v_+)}, \\ h_y = -\mathrm{j}\dfrac{\hat{h}}{2}\,e^{\mathrm{j}\omega(t-z/v_+)}, \end{cases}\\ -\ \text{component:} &\begin{cases} h_x = \phantom{-\mathrm{j}}\dfrac{\hat{h}}{2}\,e^{\mathrm{j}\omega(t-z/v_-)}, \\ h_y = \mathrm{j}\dfrac{\hat{h}}{2}\,e^{\mathrm{j}\omega(t-z/v_-)}. \end{cases}\end{aligned}\right\} \quad \dots\dots \quad (8)$$

On substituting these expressions in (7) and employing (7a), we find that the two components are propagated as though they were media with, respectively, relative permeabilities of

$$\left.\begin{aligned}\mu_+ &= p + q = 1 + \frac{\gamma M_s}{-\omega + \gamma H_z}\\ \text{and}\qquad \mu_- &= p - q = 1 + \frac{\gamma M_s}{\omega + \gamma H_z}.\end{aligned}\right\} \quad \dots\dots \quad (9)$$

It may be seen that μ_+, which is the permeability for that component for which the vector h rotates *with* the spin precession, will show an anomaly if $\omega \approx \gamma H_z$; this is the gyromagnetic effect. With μ_-, on the other hand, there is no such anomaly. The difference between μ_+ and μ_- produces a difference between the rates of propagation v_+ and v_- of the two circularly polarized components ($v = c/\sqrt{\varepsilon_r \mu_r}$), as a result of which the plane of polarization of the plane-polarized wave is rotated. This is the Faraday effect, which is made use of in Rayleigh's experiment and in the directional insulator for microwaves described earlier.

The rotation Θ per unit of length of the material is:

$$\Theta = \frac{1}{2}\,\omega\left(\frac{1}{v_-} - \frac{1}{v_+}\right) = \frac{\omega}{2c}\sqrt{\varepsilon_r}\left(\sqrt{\mu_-} - \sqrt{\mu_+}\right) \quad \dots \quad (10)$$

and can be calculated with the aid of eq. (9). If $\omega > \gamma H_z$, Θ is positive, i.e. looking in the direction of propagation, which in this in stanceis also the direction of magnetization, the rotation is clockwise. For $\omega \gg \gamma H_z$ and $\gg \gamma M_s$, Θ is practically independent of the frequency of the wave, namely $\Theta = \gamma M_s \sqrt{\varepsilon_r}/2c$.

It may perhaps be useful, in conclusion, to make a few remarks on the formulae and the physical assumptions on which the latter are based.

The non-reciprocal behaviour of magnetized ferroxcube is expressed in the non-diagonal terms $\mathrm{j}qh_y$ and $-\mathrm{j}qh_x$ in formulae (7), which are opposite in sign. It is also apparent from the analogy with equations (12) in the article cited in note [3].

When applying formulae (7) a number of points must be kept in view. At first sight there is a tendency to regard the occurrence of the denominators $\gamma^2 H_z^2 - \omega^2$ in (7a) as the expression of gyromagnetic resonance, giving the resonance frequency in the ferromagnetic medium as γH_z, as would be the case for a free electron located in a field H_z. That this conclusion is in general erroneous can be seen from formulae (3), which shows ω_p to be related in a far more complex manner with H_z ($= H_e - N_z M_s$) and M_s, notwithstanding the fact that in the ellipsoid, to which formula (3) refers, equations (7) are equally valid. The underlying cause can be stated as follows: the components h_x, h_y and h_z represent the internal, and not the external alternating field, i.e. the external field augmented by the demagnetizing field. A contribution to this demagnetizing field is made by all the values that the components of M assume at the surface of the ferromagnetic medium, i.e. including places that may be far removed from the point considered.

In addition to the strong coupling between the spin vectors of one Weiss domain (exchange forces) and the coupling between the spins and the crystal lattice there is an extra coupling between widely separated spins, precisely because of the above-mentioned contributions to the demagnetizing field to which the spins themselves also contribute. Just as in mechanics, where the characteristic frequencies of a set of coupled oscillators is not in general the same as that of a single free oscillator so in this case the resonance frequency of the ferromagnetic medium is not the same as the resonance frequency γH_z that a free spin would exhibit in the field H_z.

The above-mentioned spin-lattice forces are not allowed for in formulae (7) and (7a); they have, however, been accounted for in article II, namely by adding to the magnetic field H an imaginary field H_A which is equivalent to the spin-lattice forces. If it is required to make formulae (7) and (7a) more complete in this respect, the vector H_A can be introduced into them too. If, for example, H_A is parallel to H_z, H_z can be replaced in (7a) by $H_z + H_A$.

Summary. A brief exposition is given of the principle of reciprocity in mechanics, optics and electricity, and cases from all three subjects are cited in which this principle is not obeyed. All these cases are based, essentially, on gyroscopic effects. Electric networks disobeying the principle of reciprocity must include a non-reciprocal element, the simplest example of which is Tellegens's gyrator. In the propagation of electromagnetic waves, non-reciprocal effects are obtained when magnetic rotation of the plane of polarization or related phenomena are involved. In materials like ferroxcube these effects occur as a consequence of the phenomenon of gyromagnetic resonance. A description is given of how this phenomenon can be utilized in the construction of waveguides which give a different attenuation in the two directions (directional isolators), or a phase difference of 180° in the two directions.

An appendix shows (after Polder) how the formula for Faraday rotation can be derived from the relationships between the components B and H in a ferromagnetic material.

FIFTY YEARS OF THE HIGH-PRESSURE MERCURY VAPOUR LAMP

by W. ELENBAAS.

621.327.534.2

In recent years there has frequently been occasion to review the historical growth of important technical developments. While this Review makes no attempt at completeness in this respect, the following article, by one of the pioneers of the high-pressure mercury vapour lamp is thought to have an intrinsic interest for the reader, quite apart from its commemorative aspect.

In the summer of 1906 there appeared in the Annalen der Physik a paper by Küch and Retschinsky on the production of light by a discharge in mercury vapour under high pressure [1]). The discharge took place in a silica tube with two pools of mercury acting as electrodes (*fig. 1*). Ignition was brought about by tilting the tube, so that the electrodes were connected by a thread of liquid mercury; the breaking of the connection caused an arc to be set up. By adjusting the power fed in and the heat dissipation of the electrode spaces, Küch and Retschinsky obtained vapour pressures of several atmospheres in the tube, whereby a luminous efficiency of about 50 lumen/watt was reached. This was the first time that light had been produced with *high efficiency* from a gas discharge — although as yet this light source was of no immediate use for the purposes of illumination. With the low pressure gas discharges, known hitherto, it had not proved possible to produce light with efficiencies[2]) better than a few lumen/watt (see also *fig. 2*). On account of the high proportion of ultraviolet in their radiation, the first high-pressure mercury vapour lamps were used mainly for medical purposes, as "sun-ray lamps".

Now, fifty years after this pioneer work, it is of interest to trace the further development of the high-pressure mercury discharge. We may divide this period roughly into halves: the first half brought forth but few changes in the original lamp, while in the second an intensive development took place which has led to the production of many widely differing types of lamps.

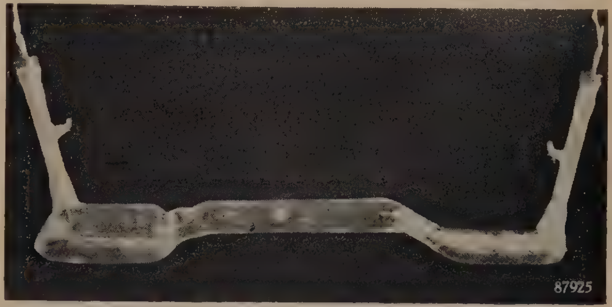

Fig. 1. The high-pressure mercury vapour lamp of Küch and Retschinsky. Ignition was accomplished by tilting the lamp. (Reproduced from Ann. Physik **20**, 563-583, 1906).

The period of intensive development started with the introduction of the oxide cathode and the addition of noble gases to the mercury vapour. The oxide cathode has been known since 1903 (Wehnelt) and had been employed in vacuum tubes, but it was not until about 1930 that the possibility of its employment in the high-pressure mercury vapour lamp became apparent. Discharges

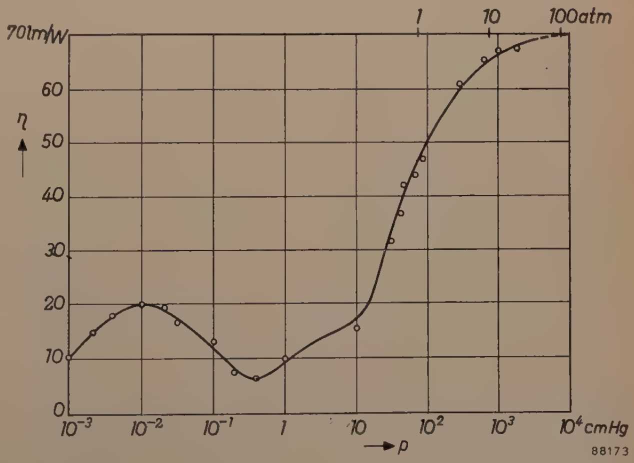

Fig. 2. Luminous efficiency η of a mercury vapour discharge, as function of the vapour pressure p, the current and the tube diameter being constant. (Reproduced in par from an article by H. Krefft and E. Summerer in Light **4**, 1-5, 1954.)

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[1]) R. Küch and T. Retschinsky, Photometrische und spektralphotometrische Messungen am Quecksilberbogen bei hohem Dampfdruck, Ann. Physik **20**, 563-583, 1906 (26th June). Temperaturmessungen im Quecksilberbogen der Quarzlampe, ibid. **22**, 595-602, 1907.

[2]) In mercury vapour under low pressue it is mainly ultraviolet rays of very short wavelength that are produced. A detailed explanation of the physics of this phenomenon may be found, for example, in an article by G. Heller, Comparison between discharge phenomena in sodium and mercury vapour lamps, Philips tech. Rev. **1**, 2-5 and 70-75, 1936.
Only long after 1906 was it learned how ultra-violet radiation might be transformed by fluorescence into visible light and how the low-pressure mercury discharge might thus be used as a light source of very high efficiency (tubular fluorescent lamps).

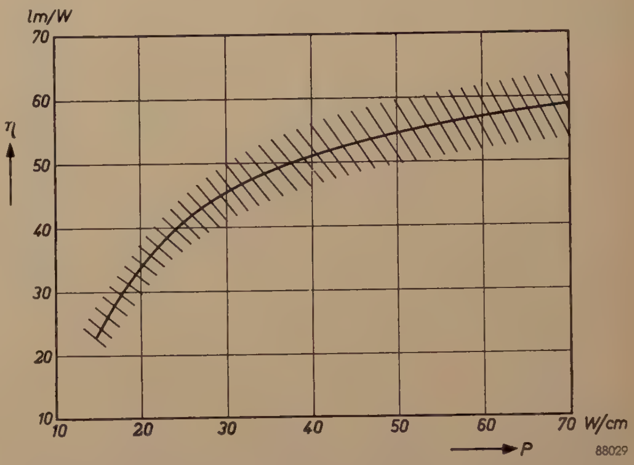
in mercury vapour under low pressure with additions of noble gases had been known since about 1910 (Claude and other). These two innovations made it possible to ignite the high-pressure mercury vapour lamp without the tilting operation and, with suitable geometry (combined where necessary with auxiliary electrodes or other artifice), the lamp could be made to ignite from a mains voltage of 220 V. In this way it became practicable to use the lamp for lighting purposes, especially the lighting of streets, open spaces, factory sheds and the like, where there was a need for a light source with very high efficiency (incandescent lamps can reach only about 15 lm/W) and where, at that time, the poor colour rendering of its light was not regarded as a serious objection.

An important feature of the new lamps was that the amount of mercury introduced into the envelope was limited to that which would just be completely vaporized once the desired pressure had been reached, the vaporization taking place as the lamp warmed up. This prevented the vapour pressure rising to an excessive value should the mains voltage or ambient temperature become too high.

The first high-pressure mercury vapour lamps for lighting purposes were made of hard glass with a high softening point (of the order of 700 °C) and not of silica as used in the lamp developed by Küch and Retschinsky. The reason was not merely the high price of silica, but also the problem of the connections through the wall of the tube, a basic and recurring problem in the history of this type of lamp. The method used by Küch and Retschinsky, viz. ground conical holes in which the terminals made a tight fit, was not suitable for a commercial product and the fusing of wires into silica was still a matter of difficulty in the 1930's.

The power of one type of these high pressure mercury lamps (type HO) [MA/V] [3]), which were supplied from the mains via a choke coil, amounted to about 400 W and the pressure inside them to about 1 atm; the actual discharge tube was enclosed in an outer envelope. In this way the lamp was made easier to handle and, when used in the open air, the discharge tube was protected against wind, so that the warming-up process and the building-up of the mercury vapour pressure were not interfered with.

In the further development of the high-pressure mercury discharge the laboratories of the various lamp factories took diverging paths. One point was of great importance for the line of development followed by Philips: the appreciation of the fact [4]) that the luminous efficiency η of a high-pressure mercury discharge, is dependent in the first instance on P, the power loading per cm of arc length, and only slightly dependent on the tube diameter and the vapour pressure once the latter has exceeded a certain value. η increases with P in the manner shown in *fig. 3.*



Fig, 3. Luminous efficiency η of a mercury vapour discharge, as function of the power load P per cm (schematic). With sufficiently high vapour pressures — higher as the tube diameter is made smaller — the observed values for different tube diameters and pressures lie within the hatched area.

This behaviour is a consequence of the contraction of the discharge. Apart from the pressure, which remains constant throughout the tube, it is the temperature that determines excitation and ionization in the high-pressure discharge, in accordance with the equations of Boltzmann and Saha (see [4]) or [2])). The temperature decreases from the axis of the tube towards the wall, owing to dissipation of heat to the surroundings. For these reasons the discharge mainly takes place in the central portion of the tube, where the temperature is of the order of 6000 °K. As a result of this contraction of the discharge, the losses are largely restricted to heat conduction losses, these being determined by the difference of temperature between the centre and the wall. If we call the heat conduction losses per cm length A, then a power $P-A$ per cm of tube length leaves the discharge in the form of radiation. Of this quantity a certain fraction g is absorbed in the mercury vapour between the contracted discharge and the wall, in the tube wall itself and in the outside air (which absorbs, for example, the ozone-forming radiation of wavelength of 1850 Å). Hence S, the measured radiation per cm of tube length, will be

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[3]) In this article, lamp types are designated first by the Philips code letters and then, in square brackets, by the code letters used in British territories and certain other countries.

[4]) W. Elenbaas, Die Quecksilber-Hochdruckentladung, Physica 1, 673-688, 1934.

$$S = (1 - g)\,(P - A) \quad . \; . \; . \; . \; . \; . \quad (1)$$

In *fig. 4*, S is plotted against P for a series of high-pressure mercury discharges in silica tubes. It will be seen that the points fit equation (1) very closely,

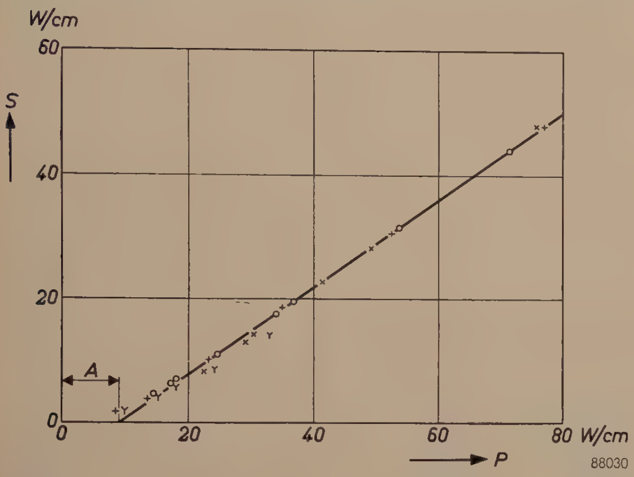

Fig. 4. Total radiation S per cm of arc length from the high-pressure mercury vapour discharge, as function of P, the power load per cm, measured on a series of silica discharge lamps. The tube diameter was 2.7 cm in all cases. The different points (+,0, etc) in the graph indicate a sub-series of measurements on tubes differing in the quantity of mercury they contained per cm of their length. Similar series of measurements were performed on tubes with diameters of 0.92 cm and 0.33 cm, these producing roughly the same curve.

the heat conduction loss $A = 10$ W/cm being fairly constant (i.e. independent of the power P, the tube diameter and the pressure) and the factor $1-g$ being 0.72. Consequently η the luminous efficiency, which is roughly speaking proportional to S/P, is also to a first approximation proportional to $(1-g)\,(1-A/P)$; hence, as P increases, η rises first rapidly and then less steeply. This agrees well with the curve obtained by measurement in fig. 3.

The following may serve to show that A, the heat conduction loss from the contracted discharge per cm of tube length is largely independent of the power P, the tube diameter and the pressure. If T is the temperature and λ the thermal conductivity, then the heat conducted away per second through an imaginary cylinder at a distance r from the axis will be:

$$A = -2\pi r \lambda \frac{\mathrm{d}T}{\mathrm{d}r} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

The temperature of the discharge itself varies very little from one discharge to another, since T occurs only as an exponent of e in the Boltzman equation: hence a small variation in T corresponds to a large variation of the radiation. As a consequence, the quantity $r\mathrm{d}T/\mathrm{d}r$ is practically the same at corresponding points in different discharges (in tubes of diameters a_1, a_2, for example, points r_1 and r_2 are corresponding if $r_1/a_1 = r_2/r_2$), since the wall temperature may be taken to be approximately the same in all cases. Further, λ is independent of the pressure and also independent of P, since the latter can only exercise an influence on λ through T which, as we have seen, varies only slightly from one discharge to another. Hence A is substantially independent of the power P, the tube diameter and the pressure.

From this relationship between η and P it followed that, for high luminous efficiency, it was advantageous to have a short arc for a given amount of power. It was also clear that very high brightnesses might be attained by increasing the power P per cm of arc length, for — assuming that the diameter of the discharge remains the same — the power radiated per unit of surface increases more than proportionally to P, owing to the increase in luminous efficiency. This opened up a prospect of new applications inaccessible to the incandescent lamp whose brightness is limited to about 2000 cd/cm^2 by the melting point of tungsten and whose lifetime is then only some hours or tens of hours.

At first it was attempted to obtain a high value of P by arranging for the discharge to take place in the centre of a spherical hard glass vessel. However, this turned out to be impracticable in that, with the high power involved, the bulb had to be large in diameter in order to keep the wall temperature within bounds; but then the vapour pressure had to be lower, on account of the danger that the relatively large bulb might explode. This meant a decrease in the contraction of the discharge, and the desired gain in brightness was only partially realised. Moreover, at lower vapour pressures the gradient (voltage drop per cm of discharge length) is smaller, so that in order to develop a large power per cm the current has to be made much heavier; this in its turn created difficulties with regard to the electrodes and seals.

The history of the lamp then took an unexpected turn. In the Philips Laboratory at Eindhoven tungsten wires were successfully sealed in silica [5]) with the aid of an intermediate glass, thus giving seals suitable for moderate currents. A small high-pressure mercury vapour lamp was designed on this basis, the discharge taking place in a silica tube of *capilliary* form [6]) (see *fig. 5*). The combined problem of wall temperature, tube diameter, pressure and danger of explosion was avoided with this design, inasmuch as the silica tube could be water-cooled. The resulting design was ideal for attaining high degrees of brightness. The pressure of mercury vapour in the capilliary can be allowed to become very high indeed (of the order of 100 atm.) and this makes the discharge path, already narrow, even more constricted. The voltage gradient thus becomes very large. In consequence, the load per cm can be made very high for a reasonable current value (about 1 A) which will not cause too much trouble with the seals and electrodes. Lamps of this type (SP) [MD] have been developed for cinema projectors amongst other purposes; brightnesses of about 50 000 cd/cm^2 are attained in the axis of the lamp, the diameter of the capilliary being 2 mm. With experimental forms brightnesses of 180000 cd/cm^2 — greater than that of the sun [7]) — have been attained. A further advantage of the very high vapour pressures and current densities in super-pressure lamps is the strong continuum in the spectrum of their radiation, this resulting in light of a colour rendering that is a marked improvement on that given by high-pressure mercury vapour lamps with pressures of the order of 1 atm.

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[5]) B. Jonas, The sealing of metal leads through hard glass and silica, Philips tech. Rev. **3**, 119-124, 1938.

[6]) C. Bol, W. Elenbaas, W. de Groot, De Ingenieur **50**, E91, E83 and E92, 1935.

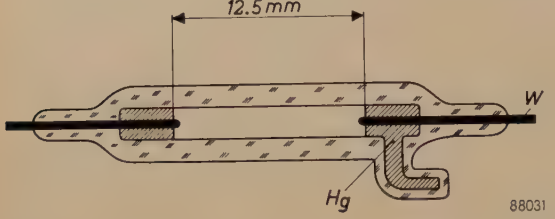

Fig. 5. Water-cooled super-pressure mercury vapour lamp of capilliary form (SP type) [MD]; it is rated at a power of 1000 W for an arc length of 12$^1/_2$ mm, the vapour pressure being of the order of 100 atm.

It may be mentioned that the capilliary form of the original SP lamp was also of importance in regard to the design of the seals. The lamp was filled with an excess of mercury which, on account of capillarity, remained lodged as a drop at each end while the lamp was burning and which ensured a uniform and relatively low temperature at the critical regions adjoining the seals. The tungsten electrodes just protude from the drops of mercury (fig. 5). Owing to the very high pressure inside the tube, the electrodes evaporated only slowly in spite of their high temperature.

Later there was a change to another, simpler, form of lead-in through silica, invented by Gabor [8]). A molybdenum ribbon, less than 20 μ thick and a few mm wide, is fused directly into the silica. The ribbon is sufficiently ductile to accomodate the difference in the expansions of molybdenum and quartz glass. This method later allowed the making of water-cooled capillary lamps containing a precise quantity of mercury which was vaporized almost completely whilst the lamp was burning [9]).

Fairly heavy currents can be passed through the silica wall by fusing in a number of molybdenum ribbons side by side. On this basis Rompe and Thouret [10]) constructed spherical silica lamps of very high brightness; this, then, is the idea mentioned on the previous page, which was difficult to realize in hard glass. In the war years these lamps, known as "compact source" lamps (CS lamps) [ME], were further developed in Germany and England for searchlights. They are still being made today in various power ratings and arc lengths for a number of special purposes.

Let us now return to the development of high-pressure mercury vapour lamps for general lighting purposes. The hard glass 400 W lamps, with vapour pressures of about 1 atm., as described earlier, had to some extent been adopted for public lighting installations. There was a demand for smaller units: 250 W and even 150 W lamps appeared, but for these wattages the advantage over the incandescent lamp in the matter of efficiency was less marked. The reason for this is that if, in view of the lower power, the arc-length is shortened in order to step up P and hence also η, in accordance with fig. 3, the total arc voltage becomes rather low in comparison with the mains voltage and there are excessive losses in the ballast and at the electrodes. One cannot avoid this by raising the voltage per cm of arc-length, since the reduction in diameter and/or increase of pressure that this would necessitate would mean high wall temperatures and the danger of explosion. One must therefore be content with a relatively long arc, a lower P and a lower η.

The problem was then attacked from a different point of view, basing design considerations on the super high pressure lamp. The use of a fused silica envelope for the latter made water-cooling possible by virtue of the low coefficient of expansion. This kind of cooling cannot of course be considered for general lighting purposes. Even without forced cooling, however, silica has the advantage over hard glass that its softening temperature is considerably higher. It was thus possible to take the SP lamp, omit the water-cooling, and increase the internal diameter of the silica capilliary slightly (to 4 mm), therby dissipating a P of 40 - 50 W/cm (in the super-pressure lamps 400 - 1000 W/cm were dissipated). A lamp of this type [11]) (HP 300) [MB/U 300] having an arc of length 18 mm and a mercury vapour pressure of about 20 atm. consumed 75 W and gave a luminous flux of 3000 lumen, so that its efficiency was 40 lm/W. The arc voltage was 230 V and the lamp was supplied from a transformer with an open-circuit voltage of 410 V. The tungsten lead-in wires were fused into the silica with various kinds of intermediate glasses. The silica tube was accommodated in an outer bulb having the same shape as an incandescent lamp.

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[7]) W. Elenbaas, Z. techn. Physik **17**, 61, 1936; see also Philips tech. Rev. **1**, 62, 1936.

[8]) D. Gabor, D.R.P. 573 448, 1931.

[9]) J. Kern, Z. techn. Physik **20**, 250, 1939.

[10]) R. Rompe en W. Thouret, Z. techn. Physik **17**, 377, 1936.

[11]) Philips tech. Rev. **1**, 129, 1936.

In the further development of these lamps even more water was put into the wine by using the same principle for lamps to operate on an open-circuit voltage of 220 V. For this purpose the arc voltage had necessarily to fall to 120 V, and to this end the diameter was again increased somewhat and the pressure lowered. Moreover, the arc had to be made rather longer, because the blackening at the tube ends arising during the lifetime of the lamp caused too much loss of luminous flux. Nevertheless, as regards power load per cm and efficiency, these high pressure lamps were considerably superior to the older ones made of hard glass, so much superior in fact that even the larger types of the old lamp were largely supplanted by the high pressure lamps now developed for higher power ratings (125 W, 250 W, 400 W, and 1000 W).

The small dimensions of the high pressure quartz lamps did much to open up the terrain of interior lighting for the high-pressure mercury vapour lamp. Hard glass mercury vapour lamps using an incandescent filament [12]) as stabilising element in place of the choke had already been used in England. The high power of the mercury vapour lamp by itself produced units that were too big for practical purposes but by adding a series-connected incandescent filament to the smaller quartz lamp accommodated in the existing outer envelope, a lamp (type ML) [MBT/U] of convenient size was produced which can be connected to the mains without a ballast device [13]). On account of the low efficiency of the incandescent filament, the total efficiency drops to about 20 lm/W: however the incandescent filament makes a useful contribution to the light emitted and the lamp as a whole gives quite a satisfactory colour rendering, and can therefore be used for offices, public halls, and other utility areas requiring a high illumination level.

A further advantage offered by the quartz HP lamp was that it radiated the ultra-violet portions of the spectrum, hitherto absorbed by the walls of hard glass lamps. By giving the ML lamp just described an outer envelope that transmitted ultraviolet rays, it was possible to use it as a simple and convenient source for medical irradiation purposes (MLU lamps) [MBTR/U]. Larger units for these purposes were equipped with special lamps of the high-pressure type having no outer envelope and provided with a choke as ballast; they had power ratings of 500 and 250 W ("Biosol"). These, then, are the modern counterparts of the lamp developed by Küch and Retschinsky fifty years ago and used for the same purpose.

Also of interest is the development whereby the ultraviolet radiation emitted by the discharge tube was exploited for the production of visible light; for this purpose, the inner walls of the outer envelope were covered with fluorescent powder (HPL lamps) [MBF]. This has improved the colour rendering to such an extent that the lamps have already largely supplanted the original HP lamps for street lighting purposes. The fluorescent substances employed in these lamps have been the object of intensive research. Recently red fluorescing arsenates and germanates have been put to use [14]).

The HPW lamp [MBW/U] may be regarded as the opposite to the fluorescent lamp; in this case, the mercury discharge tube is accommodated in an outer envelope that transmits no visible light but only radiation of the near ultra-violet. These lamps are used, amongst other things, for the fluorescent detection of forgeries and for special fluorescent effects on the stage, in advertising, in shop windows, and so on.

In conclusion mention may be made of a lamp type which, lying outside the mainstream of development of the high-pressure mercury vapour lamp, exploits its elongated form and particular kind of radiation. This is the photo-printing lamp. Sensitized paper, running beneath such a lamp of length somewhat greater than the paper breadth, is exposed rapidly and evenly. If a moderate paper speed is acceptable, the load per cm need only be relatively low and hence one can revert to the use of hard glass. Versions of such lamps exist in both

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[12]) W. H. Le Maréchal and J. N. Aldington, Brit. Pat. No. 447 428, 1936. Once the arc voltage has reached its full value, part of the incandescent filament is short-circuited by a bi-metallic relay.

[13]) K. Larché and E. Summerer, Licht **10**, 172, 1940. Also J. Funke and P. J. Oranje, The development of blended-light lamps, Philips tech. Rev. **7**, 34-40, 1942.

[14]) J. L. Ouweltjes. W. Elenbaas and K. R. Labberté, A new high-pressure mercury vapour lamp with fluorescent bulb, Philips tech. Rev. **13**, 109-118, 1951-52.

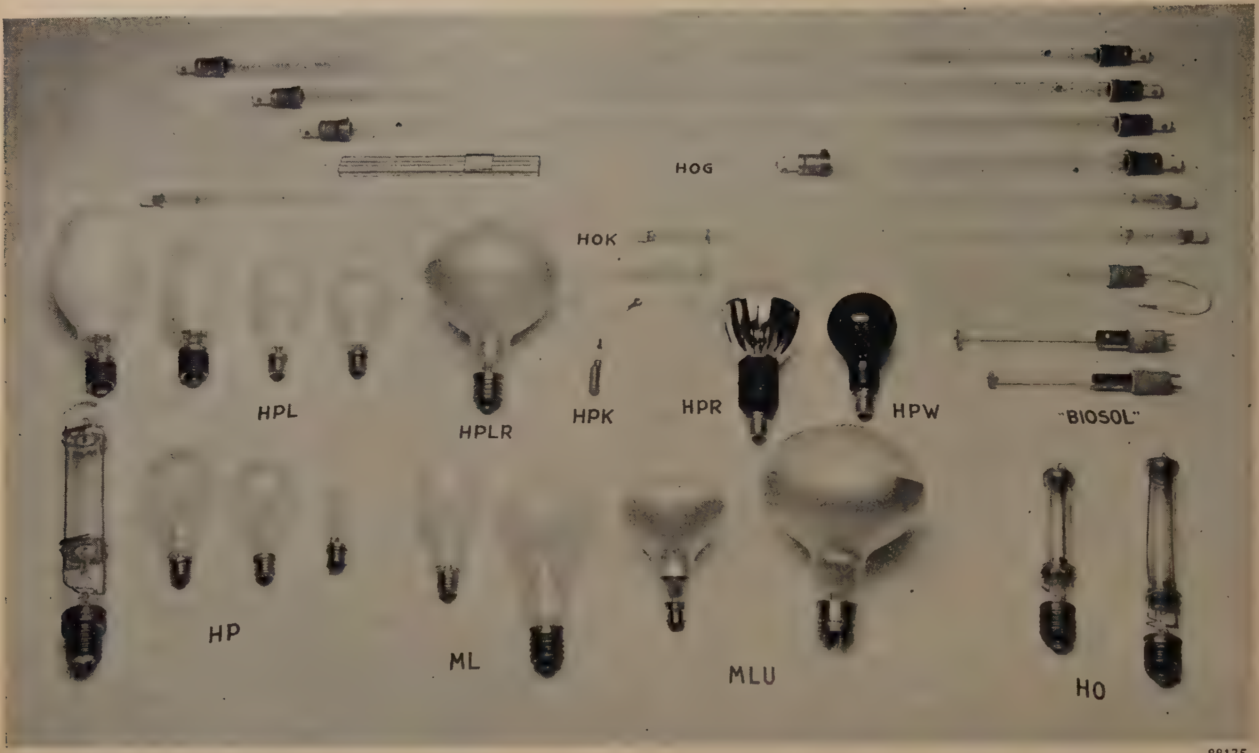

Fig. 6. A varied collection of lamps of the high-pressure mercury vapour family. In addition to the types mentioned in the text, three other lamps are shown: the HPK lamp, i.e. a high pressure discharge tube without an outer envelope, used as a source of ultraviolet radiation of very short wavelength (2537 and 1850 Å), and the HPR [MBR/U] and HPLR [MBFR] lamps, which are provided with an internal reflector.

hard glass (HOG) [MA/U] and quartz (HOK) [MB/U], and of various dimensions and power ratings.

It will thus be seen that the lamp invented by Küch and Retschinsky has given birth to a whole family of high-pressure mercury vapour lamps suitable for all kinds of different applications. Photographs of some the lamps are reproduced in *figs.* 6 and 7. Development continues in the direction of higher power ratings and higher brightness values and of special forms such as lamps having built-in reflectors, and so on.

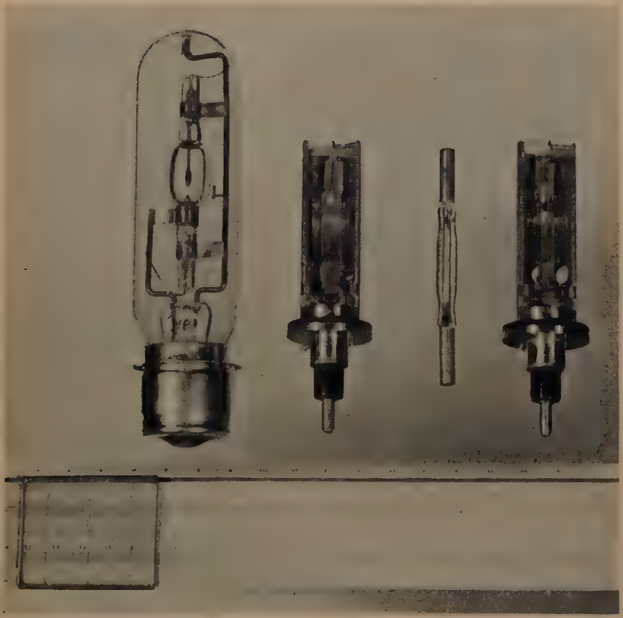

Fig. 7. Mercury vapour lamps which work under very high pressures. From left to right: a compact source lamp rated at 150 W; a 500 W super-pressure lamp (in reflector) for A.C. supply and water-cooling; a 900 W super-pressure lamp for forced air-cooling; a 1000 W super-pressure lamp for DC supply and water-cooling. The last three types are used for laboratory purposes, for cloud-height meters on airfields and for cinema projectors respectively.

Summary. Review of the development of different types of high-pressure mercury vapour lamps from the lamp designed by Küch and Retschinsky in 1906 and used as a "sunray lamp". The relationship between luminous efficiency (and brightness) and the power load per cm of arc-length is discussed, this being fundamental in the design of super pressure lamps with their extremely high brightness values: up to 180000 cd/cm^2. There follows a discussion of the considerations that led to high pressure lamps and their derivatives, the ML [MBT/U], HPL [MBF] and HPW [MBW/U] lamps. Mention is also made of the "Biosol", the HOK [MB/U] and HOG [MA/U] photo-printing lamps and the spherical "compact source" lamps.

A MAGNETODYNAMIC GRAMOPHONE PICK-UP

II. FREQUENCY CHARACTERISTICS

by N. WITTENBERG.

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The frequency response is all-important in gramophone reproduction, as in all fields of sound reproduction. It is not possible however, to consider the frequency characteristic of a pick-up as such, because the frequency response depends not only on the pick-up but also on the properties of the gramophone record. A further complication is that, for high frequencies, the response is dependant on the position of the pick-up on the record. These and other questions are discussed here with reference to the magnetodynamic pick-up described in Part I of the article.

The new pick-up working on the magnetodynamic principle, type AG 3020/21 (fixed coil, moving magnet), has properties that make it well-suited to both professional and non-professional use. Its design was the subject of Part I of this article [1]). In the present part of the article we shall go more closely into some properties of the pick-up.

The frequency characteristic

The frequency characteristic of the system pick-up - gramophone record is defined, for this type of pick-up (signal proportional to needle velocity), as the signal voltage induced (r.m.s. value E) as a function of the frequency f, when the sinusoidal recording of the test record is such that its generating point has constant peak velocity $\hat{v}$. From this characteristic we may deduce the required frequency response of the associated amplifier in order that the loudspeaker shall give as faithful a reproduction as possible of the original recorded sound.

Most record manufacturers work with the characteristic marked B in *fig. 1* in the making of long-playing records. The curve gives the relationship between frequency and the recording velocity to be recorded on the disc (i.e. constant input voltage on the first amplifier). Since the voltage from a magnetodynamic pick-up is proportional to needle velocity, for a record cut in this manner the characteristic of the reproducing channel must be the reciprocal of B; this is the curve marked A in fig. 1 [2]).

Using a test record [3]) with stepwise frequency bands and recording velocities in accordance with B [4]) — it is possible to determine the frequency characteristic of a pick-up in combination with this record by measuring the voltage produced at each of the recorded frequencies, which are known.

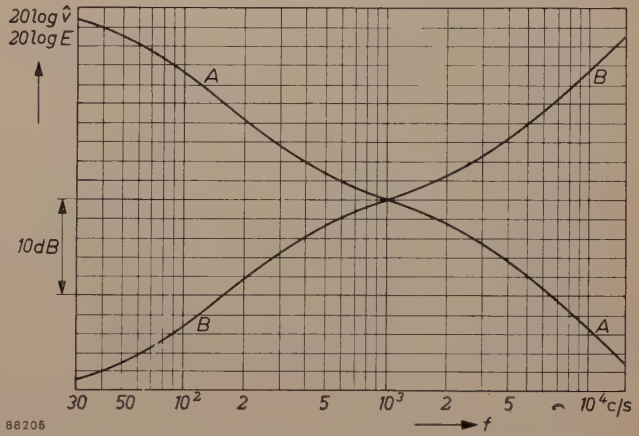

Fig. 1. A: frequency characteristic of a reproduction channel for gramophone records, largely accepted as standard.
B: the reciprocal of A; this curve shows how the modulation velocity of gramophone records should vary with f, the recorded frequency.

Reasons why the response should extend to very high frequencies

In designing the magnetodynamic pick-up the aim was to extend the frequency response to the highest possible frequencies. One may well ask what purpose is served in trying to reproduce frequencies over 15 kc/s, since few persons apart from children can hear these frequencies, and in any case they occur only very rarely in the average recording. The reasons are the following.

In an earlier article [5]) in this Review it was demonstrated that the frequency spectrum of the output voltage of a pick-up has an upper limit fixed by one of two mechanical phenomena. One of them is connected with the fact that the needle point causes elastic deformation of both groove walls (also some plastic deformation, but this is neglected here), the deformation being deeper in the convex wall (for frequencies below the needle free resonant frequency). One consequence of this is that the amplitude of the needle point is less than the amplitude of the groove, i.e. there is a *static tracing loss.* The loss is greater the shorter the wavelength λ recorded on the disc; at a certain wavelength λ_{co}, the cut-off wavelength, the loss is so great that the output voltage drops to zero. The other phenomenon that may impose an upper limit on the frequency spectrum is *resonance.* This can be either a resonance of the pick-up assembly itself [6]) or it may be the groove/needle resonance (stiffness of the groove wall/effective mass at needle point) dealt with in the article cited in footnote [5]).

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[1]) N. Wittenberg, A magnetodynamic gramophone pick-up, I. Construction. Philips tech. Rev. **18**, 113-122, 1956/57.

[2]) A is the proposed "standard reproduction channel"; see Philips techn. Rev. **17**, 104, 1955/56, or G. Slot, "Microphone to ear", Philips technical Library, Popular Series, 1956, pp. 46-49.

[3]) Test records of various types are available; the sound is recorded with a known modulation velocity, and the pitch may change continuously or in steps.

[4]) The Decca test record LXT 2695 meets this requirement satisfactorily.

[5]) J. B. S. M. Kerstens, Mechanical phenomena in gramophone pick-ups at high audio frequencies, Philips tech. Rev. **18**, 89-97, 1956/57 (No. 3)

In many pick-up designs the frequency spectrum is limited by one of the resonances of the pick-up assembly, but in the magnetodynamic pick-up these appear only at frequencies higher than that of groove/needle resonance. It is therefore the groove/needle resonance that imposes the upper limit on the spectrum of the magnetodynamic pick-up. In the article [5]) its effect is referred to as *dynamic tracing loss.*

Now, to answer the question as to the purpose of reproducing frequencies above 15 kc/s, let us assume that it is a resonance frequency f_{res} that forms the upper limit to the spectrum, which therefore does not go up to frequencies where static tracing loss is dominant. If f_{res} falls within the audible range the result is that reproduction is "coloured", that is, a sound with the frequency of the resonance is heard continuously in the background, the sound being stronger the less the damping. This "colouring" is due to sounds at this particular frequency being emphasized by resonance. It is equally due to ringing effects each time the resonant system is excited. Not only music and speech are subject to "colouring" but also the *noise*, however faint, that is always present to some extent in the record. Accordingly, the noise heard in reproduction will be less *troublesome*, if not less strong, *the higher the limiting resonance frequency is made.*

A second argument for raising f_{res} above the audible range is that large phase shifts occur in the neighbourhood of that frequency. These affect the reproduction of the sudden bursts of sound that frequently occur in music; phase shifts cause these transients to be lost to a great extent in reproduction.

As the spectrum is broadened out, the easier it becomes to pick out individual instruments. To some extent the effect is analogous to the better and better impression of reality given by looking at a series of half-tone photographs of the same scene but printed from blocks of increasingly finer screens. This is a third reason for putting f_{res} above the audible range.

But even if the lowest resonant frequency lies at, say, 20 kc/s, there is still no guarantee that the needle will faithfully follow the groove at very high audio frequencies, should these be present in the recording. Static loss has the consequence that, with increasing frequency, reproduction gradually falls off; at f_{co} and beyond, it inevitably drops to zero, f_{co} being the frequency corresponding to the cut-off wavelength λ_{co}. In general, the frequency f and the wavelength λ are connected by the formula $f = V_g/\lambda$. V_g is the velocity with which the groove passes under the needle, and it is proportional to the diameter of the circle formed by the groove being traced. Hence, as the pick-up moves inwards towards the centre of the disc, f_{co} gradually becomes lower. If f_{co} falls below the resonant frequency that has previously imposed an upper limit to the spectrum, from that moment onwards it is f_{co} that imposes the limit.

We shall now investigate these phenomena as they affect our pick-up, in the light of measurements carried out upon it.

Measurements on the magnetodynamic pick-up at high audio frequencies

Fig. 2 gives the frequency characteristic of the AG 3020 pick-up as obtained by measurement with the aid of two test records [7]); on these records frequency bands of 20 kc/s, 18 kc/s, 16 kc/s, etc. are recorded with wavelengths such that there is no noticeable tracing loss, and with constant recording velocity (except for the 20 kc/s band where, according to the manufacturer, the recording velocity was 11 dB too low; it was indeed found that at 20 kc/s the voltage given was about 11 dB too low). It will be seen from the diagram that no limiting resonance occurs below 20 kc/s; that groove/needle resonance does not occur below that frequency is to be

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[6]) See under the heading "*The needle arm and the needle*" in Part I of this article [1]) (p. 117), where lateral resonance and torsional resonance are discussed.

[7]) Deutsche Grammophon-Gesellschaft Nos. 68 421 and 68 439. These are 12″ shellac records playing at 78 r.p.m., which together cover the range of frequencies from 20 kc/s down to 30 c/s.

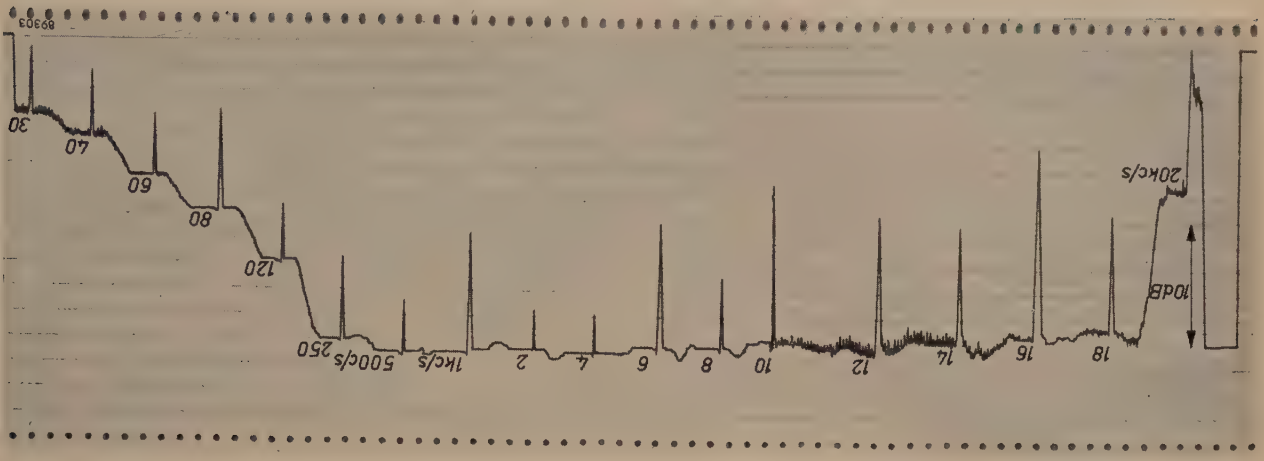

Fig. 2. Trace (on logarithmic scale) of voltage delivered at different audio frequencies by a non-loaded AG 3020 pick-up during the playing of shellac test records DGG 68 421 and DGG 68 439 [7]). The wavelengths cut in these discs are everywhere greater than the cut-off wavelength. The vertical force F_v was 0.1 newton.
On the extreme left is the 1000 c/s voltage reference level. The measurements proper begin at f = 20 kc/s (where, according to the manufacturer of the records, the modulation velocity during recording was 11 dB too low). The inverse peaks in the trace are frequency markers; only to the immediate right of each mark have the frequency and modulation velocity the right values. Modulation velocity is constant from 18 kc/s to 250 c/s and decreases at lower frequencies.

attributed, for one thing, to the high elastic modulus of the shellac material of which the test records are made.

The microgroove pick-up, AG 3021, — the same pick-up system apart from the needle — can be examined using another test record; this too has frequencies of up to 20 kc/s recorded, but with shorter wavelengths [8]). The curve *a* in *fig. 3* is that supplied by the manufacturer of the record and gives the recording velocity $\hat{v}$ as a function of frequency, as determined by optical methods; also indicated in the diagram is the wavelength λ for each of the seven bands from 20 to 8 kc/s. An ideal pick-up would have an output voltage curve with the same shape as curve *a*. Instead, we find the characteristic marked *b*; it seems that about 18 kc/s a small resonance occurs which causes the characteristic to rise by a few decibels, after which it falls rapidly. It is not permissible to attribute the difference between *b* and *a* entirely to resonance, however, for a certain amount of static tracing loss may be involved. To separate this latter from resonance effects (dynamic tracing loss) we make use of the following artifice.

Referring to the wavelength scale (top right, fig. 3), *b* gives the voltage as a function of λ. In order to eliminate resonance phenomena we shall associate the same wavelengths with frequencies at which no resonance occurs by making the disc turning more slowly. If we make the speed 10 r.p.m. (instead of $33\frac{1}{3}$ r.p.m., the speed at which curve *b* was obtained), the highest frequency reproduced becomes 6 kc/s; the form of *b* makes it unlikely that any resonance will occur below that frequency.

The voltages measured at 10 r.p.m. are given in curve *c* as a function of wavelength (*not* of frequency); the ordinates have been corrected for the lower voltages measured resulting from the lower speed. Hence *c* gives, as a function of λ, the *needle*

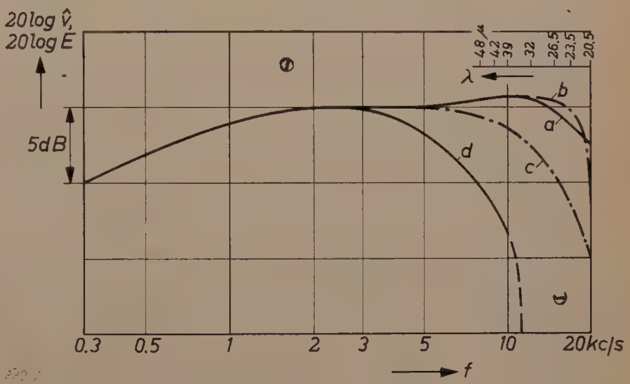

Fig. 3. *a*) Modulation velocity $\hat{v}$ as function of frequency f for the Cook 10A synthetic resin test record (curve supplied by the manufacturer) [8]). *b*) Voltage E delivered by non-loaded AG 3021 pick-up during playing of Cook 10A record at $33\frac{1}{3}$ r.p.m.; wavelength scale appears at top right. *c*) E as function of λ, for the same record turning at 10 r.p.m.; ordinates have been corrected to allow for the low rate of rotation. The range of wavelengths from 20.5 to 48 microns is recorded in grooves of diameters from 24 to 22 cm. *d*) curve of E as function of f, as reconstructed for the innermost groove, which has a diameter of 12.5 cm. The vertical force used in obtaining curves *b*, *c* and *d* was 0.1 newton.

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[8]) Test record Cook 10A (made by Cook Laboratories), a 10″ synthetic resin microgroove disc playing at $33^1/_3$ r.p.m.

point velocities occurring at the recording velocities of *a* but without interfering resonances. The difference between *a* and *c* is therefore the static tracing loss. In the particular conditions in which the measurements were carried out (radius of curvature of the diamond needle point 25 μ; vertical needle force $F_v = 0.1$ N; record of synthetic resin) static tracing loss becomes perceptible at wavelengths shorter than about 50 μ.

The full curve in *fig. 4* is the static tracing loss plotted as function of λ. The function is expressed by equation (10) of article [5]):

$$\hat{y}_s = \hat{y}_{co}\left\{1 - \left(\frac{\lambda_{co}}{\lambda}\right)^2\right\}$$

where $\hat{y}_s$ is the amplitude of the needle point in the absence of resonance, and y and λ are the amplitude and wavelength of the groove cut in the record. By inserting various values of λ and the corresponding values of $\hat{y}_s/\hat{y}$ given in fig. 4 we can determine λ_{co}, the wavelength at which the velocity of the needle point is zero and at which therefore the pick-up ceases to deliver a voltage. In this way we find that $\lambda_{co} = 16$ μ.

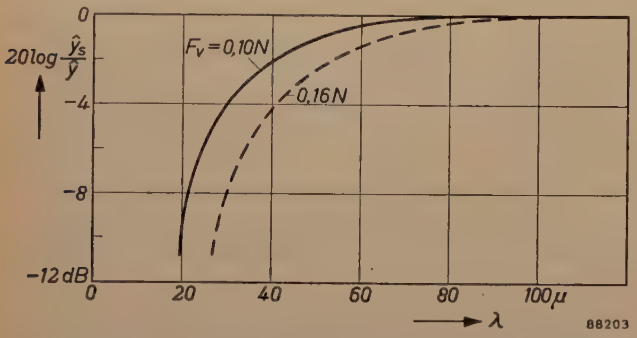

Fig. 4. The static tracing loss 20 log $\hat{y}_s/\hat{y}$, as derived from curves *a* and *c* in fig. 3, plotted against the groove wavelength λ for vertical forces F_v of 0.10 and 0.16 N. The cut-off wavelength becomes longer as F_v is increased.

For a given set of conditions (radius of curvature of needle point 25 μ; $F_v = 0.1$ N; record of synthetic resin having an elastic modulus 3.3×10^9 N/m²), equation (11) of article [5]) gives the following relation between cut-off frequency f_{co} and groove velocity V_g in m/sec:

$$f_{co} = 55\,000\ V_g \text{ c/s}.$$

Hence $\lambda_{co} = V_g/f_{co} = (1/55\,000)$ metres $= 18$ microns. Considering the errors involved the measurements described, the fact that extrapolation has to be used, and the uncertainty in the value of the modulus of elasticity, which is considerably dependent on temperature, the agreement between calculation (18 μ) and measurement (16 μ) is satisfactory.

Equation (17) of article [5]) states that λ_{co} is proportional to the cube root of the vertical needle force F_v. We can verify this relation by repeating the measurements with another value of F_v, say 0.16 N. The cut-off wavelength to be expected would then be $(0.16/0.10)^{\frac{1}{3}}$ times 16 or 18 μ; that is, say 20 μ. The broken-line curve in fig. 4 is drawn for an F_v of 0.16 N and from this we find a λ_{co} of 22 μ. Here too, therefore, there is satisfactory agreement.

Let us return to fig. 3 and compare curves *b* and *c*. The difference between them is the dynamic tracing loss, which arises on account of a resonance phenomenon at about 18 kc/s, where the difference is at its greatest. The assumption that this resonance is that of the groove/needle system (stiffness of groove wall and effective mass at needle point) can be justified as follows.

The resonant frequency of a damped vibration is given by:

$$f_{res} = f_0 \sqrt{1 - \frac{1}{2Q^2}} \quad \cdot \cdot \cdot \cdot \cdot \quad (1)$$

in which f_0 is the natural frequency of the system and Q is the quality factor. A good approximation for f_0 is $\sqrt{S/m}/2\pi$. In accordance with equation (15) of article [5]), the stiffness of the groove wall is:

$$S = \frac{3}{2}\frac{F_v}{a_0\sqrt{2}}.$$

Taking $F_v = 0.1$ N and a_0 (depth of penetration in the unmodulated groove wall) $= 2 \times 10^{-6}$ metre we find that $S = 53\,000$ newtons/metre, and taking $m = 3 \times 10^{-6}$ kg we obtain $f_0 = 21.2$ kc/s. From fig. 3 we see that the greatest difference between *b* and *c* is 6 dB, which corresponds to a Q of 2. These values of f_0 and Q, inserted in equation (1), produce a f_{res} value of 19.8 kc/s, which is near enough to the resonance observed at 18 kc/s to make it probable that this resonance is that of the groove/needle.

We see from fig. 3 that the resonance effect is stronger than might be mistakenly supposed from curves *a* and *b*, and that over a big range of frequency it compensates the static tracing loss. The question might be posed as to whether the straightness of the characteristic in fig. 2 is also due to compensation of this kind. This does not seem to be the case: if we give a slower turning speed to the shellac record with which this characteristic was obtained, we get the same line as that given at the normal speed of 78 r.p.m. The shortest wavelength on this record is 60 μ, this producing the 20 kc/s tone; this frequency is cut in a groove of about 30 cm diameter. Fig. 4, which was obtained with a synthetic resin record, shows that the tracing of this wavelength involves a loss smaller than 1 dB, so that for the shellac record, with its higher elastic modulus, it is certain that no perceptible tracing loss will arise at $\lambda = 60\ \mu$. We may therefore conclude from the straightness of the characteristic that the system is free of resonance below 20 kc/s.

Comparison of curves *a* and *b* in fig. 3 may perhaps lead to the question: what is the significance in practice of the static tracing loss? The loss is, after all, largely compensated by dynamic tracing loss (groove/needle resonance), which is determined by the material of the record, the radius of curvature of the needle, the vertical force F_v and the effective mass — that is to say by factors that are always the same for a given gramophone and type of record. Apart from this, it would be an easy matter to correct insufficient or excessive compensation in the amplifier. But what has to be borne in mind is that static tracing loss is a *direct* function of wavelength, and only an *indirect* function of frequency, via the relation $\lambda = V_g/f$. Consequently the frequency at which a given combination of record and pick-up will exhibit a certain static loss is dependent on the groove velocity V_g and thus on the diameter of the groove.

On the record used for the measurements of fig. 3, the range of frequencies from 20 kc/s to 10 kc/s is registered in grooves having a diameter of from 24 cm to 22 cm; consequently, curve *b* in fig. 3 is valid only for that portion of the disc. Further towards the edge of the record the same wavelengths produce higher frequencies; here, therefore, there is stronger reproduction of high frequencies than from grooves nearer the centre. It would be possible to obtain the characteristic for the innermost grooves by using a test record on which wavelengths of from 20 to 50 μ were cut in grooves having a small diameter. Such a disc is not available, but we can reconstruct the characteristic in question from curves *a* and *c* by taking into account that the frequency at which static tracing loss has a given value is proportional to the diameter of the groove. Characteristic *d* in fig. 3 has been constructed in this manner; it applies to the innermost groove of a long-playing record, which has a diameter of 12.5 cm. The cut-off frequency, which is 23-26 kc/s for curve *b* ($\lambda = 18$ or $16\ \mu$), is only 12-13.5 kc/s for curve *d*. These frequencies are below the resonant frequency and hence there can be no compensation due to resonance (negative dynamic tracing loss) above 12-13.5 kc/s in the innermost grooves.

The foregoing has attempted to show that there is no point in supplying a frequency characteristic with a pick-up without at the same time specifying the test record used and the value of F_v the vertical force during the measurements. Even then, the characteristic gives no more than an overall impression of what may be expected from the playing of a normal record; it must be remembered that static tracing loss is dependent on the groove velocity, that is, on the diameter of the groove being traced. Fig. 3 shows that this effect becomes perceptible at a frequency as low as 3 kc/s.

Reproduction of very low frequencies

In the foregoing attention has only been given to the upper register. We shall now say a word about the reproduction of very low frequencies. In the magnetodynamic pick-up, unlike the electrodynamic there is no objection to the use of a coil with a large number of turns. An input transformer — essential for the electrodynamic pick-up — is thereby rendered superfluous. The transformer is an expensive item if good reproduction of low audio frequencies is required for its primary then has to have a high self-inductance. The fact that there is nothing to set a lower limit to the frequency spectrum of the magnetodynamic pick-up is, of course, favourable for the reproduction of musical sounds of the lowest pitch, but at the same time it leaves the way open for undesired low frequencies. Vibrations of very low frequency arise through mechanical shock or vibration; they may arise in the gramophone itself or in the recording equipment (in the latter case they form part of the recording). Although these frequencies are often below the limit of audibility (in the region of 10 c/s, say), they can be very troublesome in that the unwanted voltage they cause may take up a large part of the grid swing in the output stage; when this happens even a weak signal, in combination with the unwanted voltage, may overload the amplifier. The difficulty is removed by suitable design of the amplifier, but to go into details would be to depart from the framework of the present article.

Effect of the electrical load on the frequency characteristic of the pick-up

The load across the pick-up during the above determinations of the characteristics was very small. In normal use, however, there is a greater load on the pick-up — not only that of the amplifier input impedance, but also that of a capacitance of about 250 pF, consisting mainly of the capacitance of the connecting lead between pick-up and amplifier. Since the internal impedance of the pick-up is partly due to a self-inductance of 0.6 H, a tuned circuit is formed, the resonant frequency of which is in the vicinity of 13 kc/s; this resonance, being inside the audible range, is undesirable. By making the right choice of load impedance, however, this resonance can be damped to a point where it practically ceases to be effective. Two frequency response curves appear in *fig. 5*: the first is curve *b* from fig. 3, as obtained with a parallel capacitance of some tens of pico-farads and a load impedance of 0.5 MΩ; curve *e*, the second characteristic, was obtained by using the same test record with a parallel capacitance of 250 pF and a load impedance of 68 kΩ. The difference between the two curves becomes greater than 2 dB only above 14 kc/s. With the majority of records the difference is scarcely audible; for this reason a value of 68 kΩ is recommended for the terminating resistance.

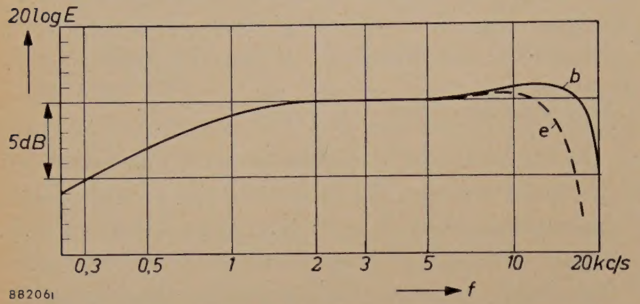

Fig. 5. The effect of the pick-up's electrical load on its frequency characteristic. Curve *b* was obtained with a pick-up type AG 3021 subject to practically no load; for curve *e* the pick-up had a load consisting of 68 kΩ in parallel with 250 pF, the circumstances otherwise being the same. Curve *b* here is identical to curve *b* in fig. 3.

Non-linear effects

When short wavelengths — that is, high frequencies cut in small-diameter grooves — are traced, effects become perceptible which, for the sake of simplicity, were not taken into consideration in the article referred to under 5). Thus strong non-linear tracing distortion may arise 9) because, for example, the peaks of a sinusoidal groove are so sharp that the needle point no longer fits into them. The main consequence is that third harmonics are set up. Even if their frequencies are above the cut-off frequency, it is still possible for these harmonics to be reproduced, for the cut-off frequency is determined by the static tracing loss which itself depends only on the actual pattern cut in the disc: hence any frequencies due to distortion in the playback process are not effected by the cut-off frequency. This non-linear effect may partially compensate harmonics recorded on the record but lost on account of static tracing loss, and in this way it may give rise to an impression of better reproduction of the upper register. However, these phenomena have been so little investigated that it is not possible to go into them here.

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9) J. A. Pierce and F. V. Hunt, On distortion of sound reproduction from phonograph records, J. Acoust. Soc. America **10**, 14-28, 1938/39. W. D. Lewis and F. V. Hunt, A theory of tracing in sound reproduction from phonograph records, ibid. **12**, 348-365, 1940/41.

Summary. Part I of this article dealt with the design of the magnetodynamic pick-up, types AG 3020/21. In Part II above the author puts forward a number of arguments for extending the frequency response to above 15 kc/s, as has been done in the magnetodynamic pick-up. In the course of the discussion on the frequency characteristic for the upper register, a method is described of separating static and dynamic tracing losses, these being a wavelength and a frequency effect respectively. With records of synthetic resin, static tracing loss exhibits a cut-off frequency of about 24 kc/s where the groove has a diameter of 24 cm, and of about 12 kc/s for the innermost groove; dynamic tracing loss, on the other hand, is connected with a groove/needle resonance at about 18 kc/s. A word is also devoted to reproduction at very low frequencies, to the effect of the electrical load on the pick-up and to non-linear effects.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to Philips Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2.

2322: G. W. Rathenau and J. F. Fast: Initial permeabilities of sintered ferrites (Physica 21, 964-970, 1955).

It has been shown (Wijn, Went) that the initial permeability of sintered NiZn ferrites is mainly caused by simultaneous rotation of the spins. This view is supported by the present investigation, especially by the evidence of experiments in which the spin distribution was anisotropic in the absence of external stresses. Also, the influence of stress on the initial permeability can be accounted for by considering simultaneous spin rotation only. Under certain circumstances a contribution of domain wall movement to the initial permeability must be taken into account. This is the case, for example, when the material has been demagnetized by heating to temperatures above the Curie temperature and cooling.

2323: A. H. Boerdijk: Het mechanisch evenwicht van een lichaam dat over een vlak kan rollen (Simon Stevin **30**, 193-231, 1955). (The equilibrium of a body that can roll on a surface; in Dutch).

A rigid body B' is placed upon a rigid surface O in a position of mechanical equilibrium with respect to a gravitational force acting on the body. The stability of this equilibrium is investigated for the case of small rolling or spinning movements of B' over O. Sufficient conditions for stability and lability are expressed inter alia in terms of the principal radii of curvature of O and of the surface B of B' at the contact point or points. It is shown that there exists an infinite number of combinations of bodies and surfaces showing neutral equilibrium, the case of a sphere on a horizontal plane being a special one. If either B or O are given, neutral equilibrium is always possible if there is more than one point of contact. In the case of one point of contact neutral equilibrium is possible only if B and O satisfy certain partial differential equations.

2324: H. J. J. van Boort and M. Klerk: High frequency oscillations in low pressure mercury arcs (Appl. sci. Res. **B5** ,69-74, 1955).

The influence of the associated circuit of a low-pressure tubular fluorescent lamp on the propagation of the noise generated in the lamp is discussed. Two types of noise, cathode noise and anode noise, have been distinguished by the use of an electronic method. The cathode-noise is subjected to a more detailed investigation, particularly the re-ignition noise. A hypothesis is put forward regarding the manner of generation of two different types of re-ignition noise.

2325: W. Elenbaas: The behaviour of the high pressure discharge in Xe-Hg mixtures (Appl. sci. Res. **B5**, 205-209, 1955).

Spectral data and voltage gradients have been determined for a series of Xe-Hg discharges at constant loading. With increasing Hg%, voltage gradient and Hg spectrum intensity increase whilst the Xe spectrum intensity decreases. The results are explained by a consideration of the variation in discharge temperature, leading to theoretical values in good agreement with experimental results.

2326: H. G. Beljers: Application de la résonance ferromagnétique dans les ferrites (Cahier de Phys. No. **62**, 43-44, October 1955).

With magnetically polarized ferromagnetic materials such as ferroxcube, the principle of reciprocity may not be obeyed. Transmission of electromagnetic waves through such a material gives rise to the Faraday effect or the Cotton-Mouton effect, depending on the mutual orientation of the transmission and the polarization. Practical applications of both possibilities are briefly indicated.

2327: J. S. van Wieringen: La résonance ferrimagnétique des ferrites à température de compensation (Cah. de Physique 45-47, 1955).

Continuation of the work reported in abstract **2114**. The gyromagnetic factors of Li-Fe-Cr spinels of two different compositions are given at 9500 and 24000 Mc/s.

2328: W. J. Oosterkamp, G. M. Ardran and others: Discussion on "image intensification in radiology" (Proc. Instn. Electr. Engrs. **102B**, 845-849, 1955).

Short discussion of design factors, quantum fluctuations and noise, problems in medical applications, etc. of X-ray image intensifiers.

2329: C. Z. van Doorn and Y. Haven: Dichroism of the F and M absorption bands in KCl (Physical Review **100**, 753, 1955).

An additively coloured KCl crystal showing the F and M absorption bands becomes dichroic after irradiation in the F band with polarized light at 77 °K. Both the F and M bands show this dichroism. A crystal which shows only the F absorption band does not become dichroic under the same circumstances. These and other experiments indicate that the M centres responsible for the M absorption are anisotropic and are oriented along the 2-fold symmetry axes. In crystals showing both F and M absorption bands, at least part of the F band must be due to M centres instead of F centres. The dichroism is attributed to reorientation of the M centres by ionic movement induced by irradiation in the F band.

R 292: S. Landsberg: A general purpose drift-free D.C. amplifier (Philips Res. Rep. **11**, 161-171, 1956).

A method for drift reduction in D.C. amplifiers is described. The advantage of the method is that the circuit which stabilizes the output voltage of the D.C. amplifier does not interfere with its characteristics. This is accomplished by comparing a fraction of the output voltage with the input voltage by means of a mechanical chopper. The chopped difference is amplified by an A.C. amplifier and its rectified output voltage is fed to the D.C. amplifier, so as to reduce the drift. Thus, the zero-point control circuit acts as a voltage stabilizer, with the input serving as a reference voltage. An experimental amplifier constructed on this principle has a gain of 8000, flat from D.C. to 300 kc/s. Input impedance at D.C. is of the order of 100 MΩ. The stability is of the order of 10 μV (with respect to the input terminals) over a period of more than five hours.

R 293: K. F. Niessen: Spontaneous magnetization and magnetic susceptibilities of an antiferromagnetic with foreign ions in only one sublattice (Philips Res. Rep. 11, 172-182, 1956).

A study is made of an antiferromagnetic in one of whose sublattices a relatively small number of original *A*-ions is supposed to be replaced by ions of another metal *B*, the moment *m'* of *B* being different from the moment *m* of *A*. The magnetization is then no longer zero. Its dependence on the temperature is investigated and also the change in the parallel and perpendicular susceptibilities due to the above replacement.

R 294: O. W. Memelink: The distribution of impurity in a semi-infinite solidified melt (Philips Res. Rep. 11, 183-189, 1956).

The transient distribution of impurity in a solidifying melt is calculated for the case of a homogeneous initial impurity concentration and constant velocity of the solid-liquid interface. The assumptions involved are: (1) the fraction of impurity concentration segregating from the liquid at the interface is constant, (2) the transport of solute from and to the interface occurs by diffusion on the liquid of semi-infinite length. The transient distribution for various values of the segregation constant is evaluated numerically.

R 295: F. K. Lotgering: On the ferrimagnetism of some sulphides and oxides (Philips Res. Rep. 11, 190-249, 1956).

The ferrimagnetic behaviour of a number of sulphides with nickel arsenide and with spinel structure has been studied. Iron sulphides of compositions between FeS and Fe_7S_8 (all nickel arsenide structure) show antiferrimagnetic properties with low sulphur content and ferrimagnetic properties with high sulphur content. These are investigated experimentally and explained in terms of order-disorder phenomena. Magnetic measurements were made on $MnCr_2S_4$, $FeCr_2S_4$, $CoCr_2S_4$ and $ZnCr_2S_4$ (all spinel structure). The properties of these sulphides and those of the corresponding oxides are discussed in relation to Yafet and Kittel's theory of ferrimagnetism. The theory is extended to cover normal spinels AB_2X_4 with one type of A-ion and one (different from A) type of B-ion.

R 296: J. Bloem: Controlled conductivity in PbS single crystals (Philips Res. Rep. 11, 273-336, 1956).

Lead sulphide single crystals were reheated under various sulphur pressures in order to influence the composition of the crystals. Electric and thermoelectric measurements after quenching showed that PbS crystals are *n*-type (conduction by electrons, surplus Pb) after heating under low sulphur pressures and *p*-type (conduction by holes, surplus S) after heating under high sulphur pressures.

For crystals doped with small concentrations of Bi or Ag, there appears to be a range of atmospheres, where the electron or hole concentrations are equal to the concentration of added Bi or Ag ions (range of controlled valency); this range is broader the lower the heating temperature. The experimental results could be explained quantitatively using the theory of Schottky and Wagner on lattice imperfections as applied by Kröger, Vink and Van den Boomgaard. In this way it has been possible to achieve some understanding of the properties of this compound; the theory may well, in principle, also be applicable to other semiconducting compounds.

R 297: F. K. Lotgering: On the ferrimagnetism of some sulphides and oxides (Philips Res. Rep. 11, 337-350, 1956).

Continuation of **R 295**. Magnetic properties of $MnCo_2O_4$, $NiCo_2O_4$, Co_3O_4, $ZnCo_2O_4$, Co_3S_4 and $NiCo_2S_4$ have been measured and are discussed in connection with the character of their chemical bonds.